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Surface Radiation Budget for Climate Applications

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Surface Radiation Budget for Climate Applications

Edited by
J. T. Suttles
Langley Research Center
Hampton, Virginia

G. Ohring
NOAA National Environmental Satellite,
Data, and Information Service
Washington, D.C.

NASA

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and Space Administration

**Scientific and Technical
Information Branch**

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PREFACE

Determination of the components of the radiative energy exchange between the Sun, the Earth (atmosphere and surface), and space is essential to an understanding of climate processes and to the development of a climate predictive capability. Over the past two decades, emphasis was placed on the top-of-the-atmosphere (TOA) radiation budget due to its importance as a driving force in the climate system, and numerous satellite experiments have been devoted to its measurement. The latest, the NASA Earth Radiation Budget Experiment (ERBE), is a multiple satellite research program that is measuring the TOA radiation budget with improved accuracy and sampling over the complete diurnal cycle.

The radiation budget at the Earth's surface has not been as amenable to remote measurement as that at the TOA, but is recognized as equally important in climate research. Surface radiation fluxes are principal elements of the total energy exchange between the atmosphere and the land or ocean surfaces, and the net radiation is a major factor in controlling the surface temperature fields. On the global scale, surface radiation exchanges produce significant influences on atmospheric and oceanic circulations. Because of its importance, a general objective of the World Climate Research Program is to reduce the large uncertainty of present estimations of the net radiation flux at the Earth's surface.

Recently, significant advances in the capability for measuring the surface radiation components have been made. As a result of the requirement for global coverage and the demonstrated feasibility of satellite techniques, emphasis has been placed on determining surface radiation from satellite measurements and using surface-based measurement for validation studies. Several promising satellite-based methods have been reported for downward shortwave flux; techniques for longwave flux and net radiation are now emerging.

To assess the current capabilities for defining surface radiation budget and to identify key topics for future research, the NASA Climate Research Program, the World Climate Research Program, and the International Association of Meteorology and Atmospheric Physics have jointly sponsored a Workshop on Surface Radiation Budget for Climate Applications. In order to provide the widest possible distribution of information resulting from the study, this report is being published as a NASA Reference Publication and as a document in the World Climate Program (WCP) series.

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*J. Tim Suttles
George Ohring*

I. EXECUTIVE SUMMARY

1. INTRODUCTION

This workshop was devoted to the problem of determining the surface radiation budget (SRB) for climate applications, particularly for studies related to the World Climate Research Program (WCRP). In this context the SRB consists of the upwelling and downwelling radiation fluxes at the surface, separately determined for the broadband shortwave (SW) (0–5 μm) and longwave (LW) (greater than 5 μm) spectral regions. The SW albedo, LW emittance, and temperature of the surface are also considered to be elements of SRB information. Because of the focus on the global climate, emphasis was placed on determining the SRB from satellite measurements and using ground-based and aircraft measurements for process studies and validation of the satellite-determined fluxes.

Some 45 scientists from Europe and North America, including specialists in climate modeling, satellite Earth radiation budget (ERB) observations, surface radiation observation, and radiative transfer, participated in the workshop (see Appendix A).

Deliberations of the workshop were structured in terms of the following:

- I. Scientific Needs and Applications
- II. Observations and Analysis
- III. Calibration and Validation
- IV. Data Sets Development

Each topic was discussed by a panel of about 12 specialists led by a panel chairman. Each chairman was requested to submit a position paper on the panel's topic in advance of the workshop; these papers are included in Appendix B. After discussions the panels prepared the summary reports which form the main body of the document. Here we outline the workshop conclusions and major recommendations.

2. SCIENTIFIC NEEDS AND APPLICATIONS

Discussions of the scientific needs and applications focused on uses of SRB data to improve our understanding of the four major climate system components: the oceans, the land surface, the atmosphere, and the cryosphere. In particular SRB estimates will be of great value in:

- (1) Diagnostic studies such as determining the role of radiation in air-sea and air-land interactions, inferring meridional heat transport by the oceans, and determining cloud-radiative forcing and the role of radiative heating in the general circulation;
- (2) Specification of boundary conditions, such as radiative energy inputs for ocean models and surface albedo for general circulation models (GCMs);
- (3) Process studies to improve parameterizations of sub-grid-scale inhomogeneities and snow-ice albedo feedback;
- (4) Validation of climate models and, in particular, their cloud generation and radiative parameterizations; and
- (5) Determination of long-term climate trends.

Thus far, very little work has been done to establish accuracy requirements for SRB. An accuracy of 10 Wm^{-2} for regional monthly averages appears reasonable for most climate applications.

Workshop recommendations concerning scientific needs and applications are to:

- (1) Maintain research on relationships between narrowband and broadband measurements to improve the accuracy of derived SRB quantities.

- (2) Continue satellite broadband measurements of ERB which include important effects, such as water vapor absorption and aerosol scattering, not observed by available operational narrowband instruments.
- (3) Improve methods for deriving all SRB components: downward and upward fluxes for both the shortwave and longwave regions, surface albedo, surface emissivity, and surface temperature.
- (4) Obtain the following data sets with high absolute accuracy for improving climate model radiation parameterizations:
 - a. spectral albedo of snow, sea ice, and soils
 - b. LW radiance spectra for clear skies
 - c. SW fluxes for effects of broken cloud conditions.

3. OBSERVATIONS AND ANALYSIS

Current observations and analysis methods for SRB reflect a much more mature satellite-based capability for SW than for LW radiation. Techniques based on single, visible channel data and tuned for specific regions yield promising results for downward SW fluxes, 20–30 Wm^{-2} (10–15%) errors in daily and 10–20 Wm^{-2} (5–10%) in monthly means. These SW methods could be improved by inclusion of additional spectral channels or broadband measurements and by development of new parameterizations, particularly for broken cloud field and surface inhomogeneities. Determination of surface albedo from visible channel satellite data appears feasible but no systematic error analysis has been performed.

Although limited in scope, several studies have demonstrated the potential for determining LW fluxes from satellite measurements and models, with resultant downward LW surface flux uncertainties of about 10–20 Wm^{-2} over midlatitude land areas. It appears feasible to improve these LW methods if information on cloud base heights and near-surface temperature profiles is provided.

For further development and evaluation of both SW and LW methods, additional surface-based observations are needed, particularly over ocean areas.

The major workshop recommendations for SRB observations and analysis from satellite measurements are to:

- (1) Establish a project to determine insolation over the tropical oceans from satellite measurements.
- (2) Conduct a pilot study to compare existing algorithms for determining SRB from satellite observations and radiative transfer calculations.

4. CALIBRATION AND VALIDATION

The calibration and validation discussions were guided by the principle that for successful validation of the SRB procedures and data sets, the satellite and ground measurements must be accurately and independently calibrated. For satellite measurements, the desired approach would include onboard calibration systems designed with absolute calibration traceability and characterization of the spectral and angular response of the instruments. Unfortunately, virtually none of the current satellite instruments used for SRB are adequately calibrated, especially for SW, and must rely on an alternative, less valid substitute calibration. The broadband measurements of the Earth Radiation Budget Experiment (ERBE) are the only satellite radiation measurements with absolute calibration traceability for Earth-viewing data. It is possible that the substitute calibration could be accomplished by looking at the same Earth scene with an identical recently calibrated sensor periodically on

Space Shuttle flights or perhaps from a calibration facility on a Space Station. Without such a capability the next best platform is a high-flying aircraft. Another option is a vicarious calibration through dedicated field experiments such as those used for the Meteosat calibration. The latter two appear to be the most viable approaches in the near term.

The calibration of ground-based sensors has been the subject of WMO activities in recent years (see, for example, WMO No. 8, 1983: Guide to Instruments and Methods of Observation) and some progress in establishing standards and operational methods has been accomplished. However, the quality and quantity of surface radiation measurements still must be substantially improved.

For validation of satellite estimates of SRB, high-quality surface measurements are essential. The surface network for SW flux measurements appears adequate over some continents but is definitely inadequate for the tropics and all ocean areas. The surface network for LW flux measurements is inadequate in all cases.

Special validation experiments for both SW and LW radiative transfer schemes are needed. Except for pure empirical regression methods, such schemes enter into all techniques for transformation of top-of-atmosphere radiance observations to SRB components. The highest priority should be given to resolving the discrepancies between LW radiation codes for clear sky conditions and to developing model parameterizations for SW radiation in broken cloud fields.

Workshop recommendations for calibration and validation for SRB determination are to:

- (1) Calibrate satellite measurements independently, either directly or by substitute methods before validating by ground or aircraft data.
- (2) Calibrate current satellite data by episodic high-altitude aircraft flights or by dedicated field measurement campaigns (vicarious calibration).
- (3) Rely only on carefully selected ground truth stations, preferably those operating with the National Radiation Centers, for satellite data validation.
- (4) Increase the number and type of surface measurements, especially over oceans and for LW component. To ensure oceans measurement, a group should be established to develop instrumentation, coordinate measurements on ships of opportunity, and manage use of data.

5. DATA SETS DEVELOPMENT

Discussion of data sets development for SRB highlighted four functions of the data system: (1) interaction and support of climate research programs; (2) validation, intercomparison, and error analysis of existing algorithms; (3) calibration of instruments; and (4) development of improved instruments, algorithms, and models. The primary data management problem appears to be the improvement of access to the large, widely dispersed data sets currently available or being produced. Basic needs are for a data catalog, improved documentation, complete calibration information, and common data format. Two research scenarios were suggested: pilot studies and surveys. Pilot studies are *intensive* multidata studies usually of limited coverage, but high resolution, to develop instruments, analysis algorithms, and radiative models and to test calibration and validation processes. Surveys are *extensive* multidata studies to obtain larger area (global) coverage over longer time periods to support climatological research.

For the initial phases of SRB research, when pilot studies will predominate, access to available data holdings can be improved by:

- (1) Creating a central catalog of relevant data to SRB which will include a record of specially collected SRB pilot data sets and analysis products.

- (2) Transmitting processed and formatted pilot study data sets for specific activities to a central SRB archive.
- (3) Taking advantage of other ongoing and planned data collection/analysis efforts (e.g., ERBE, ISCCP, FIRE, FIFE, TOGA, CLAIRE, etc.) to obtain suitable pilot study data sets.

6. PRINCIPAL RECOMMENDATION

In view of the requirements for SRB information within the projects of the WCRP, the workshop recommends the establishment of a project with an ultimate goal of determining the SRB components globally from satellite observations. As a first step, it is recommended that a pilot study be conducted to compare existing algorithms against each other and against ground truth. The global, sampled (every 30 km and every 3 hours) data sets available from the ISCCP archive may be adequate for this purpose. These satellite radiance observations, together with the ancillary data on temperature, humidity, snow cover, and ice cover provide a unique data set for research on SRB determinations from satellite observations and radiative transfer calculations. Because of the requirements of the TOGA project and the reported success of several algorithms for determining surface insolation, initial priority should be given to deriving the insolation over the tropical oceans from satellite observations. However, the proposed pilot study should also include evaluation of the other components of the surface radiation budget. The pilot study could be set up under the auspices of the ISCCP Working Group on Data Management.

II. WORKSHOP REPORT

SECTION 1

INTRODUCTION

As stated in the Scientific Plan for the World Climate Research Program (WCRP No. 2), a general WCRP objective is to reduce significantly the large uncertainty of present estimates of the total energy flux to the atmosphere from the oceans and the land surface. Net radiation at the Earth's surface is a major component of this energy flux, and its determination is vital to two important component projects of the WCRP: International Satellite Land-Surface Climatology Project (ISLSCP) (WCP 94, 1985) and Tropical Ocean and Global Atmosphere (TOGA) Project.

Planning for an ISLSCP has recently begun. The objectives of this project are to develop satellite-based methods to monitor fluctuations of the surface properties of the Earth, and to provide land-surface climatological data for the improvement of climate models. ISLSCP is concerned with radiation budget quantities at the Earth's surface, including downwelling solar radiation, surface albedo, upwelling and downwelling longwave radiation, the skin temperature and emissivity of the surface, continental snow cover, an index of vegetative cover, and soil moisture.

The oceans are distinguished optically from the continents by their low albedo and by the penetration of visible solar energy to a depth of about 100 meters. The vertical distribution of solar heating in the oceans is climatologically significant because of its effect on the mixed layer, and because it produces significant heating throughout the upper portion of the mixed layer in the tropics. By contrast, the downwelling longwave radiation from the atmosphere is essentially absorbed in the surface skin of the oceans. The energy balance at the surface of the tropical oceans is thus of major concern to the TOGA Project.

Thus far, the scientific community has emphasized the application of satellite data to studies of the space and time variability of the radiation budget at the top of the atmosphere. The net radiation patterns at the surface have been estimated primarily on the basis of a geographically biased network of reporting surface stations, many of which maintain uncertain calibration standards. In view of these limitations of surface-based radiation measurements, the feasibility of deriving global distributions of Surface Radiation Budget (SRB) components from satellite data is being examined.

This report summarizes the findings of the Workshop on Surface Radiation Budget for Climate Applications held at Columbia, Maryland, 18-21 June 1985. The SRB consists of the upwelling and downwelling radiation fluxes at the surface, separately determined for the broadband shortwave (SW), 0-5 μm , and longwave (LW), greater than 5 μm , spectral regions plus certain key parameters that control these fluxes, specifically, SW albedo, LW emissivity, and surface temperature. The workshop, which was jointly sponsored by NASA, the World Climate Research Program, and the International Association of Meteorology and Atmospheric Physics, was intended to bring together leading scientists with expertise in the theory and measurement of surface radiation by satellite and ground-based systems. The purpose was to define the uses and requirements for surface radiation budget data, to identify promising measurement techniques for producing these data, and to recommend directions for future research.

The workshop was convened by Dr. Robert A. Schiffer with Drs. George Ohring and J. Tim Suttles serving as cochairmen. It brought together some 45 leading scientists with expertise in surface radiation measurements by satellite and ground-based systems and in radiation as well as climate modeling. Deliberations were structured in terms of four topics which were discussed by a panel of invited specialists led by a panel chairman. The panel topics and chairmen are:

- I. Scientific Needs and Applications
Chairman: Dr. V. Ramanathan
Vice Chairman: Prof. S. Warren
- II. Observations and Analysis
Cochairmen: Prof. E. Raschke and Prof. T. Vonder Haar
Vice Chairman: Dr. K. Hanson
- III. Calibration and Validation
Chairman: Prof. H. Grassl
Vice Chairman: Dr. J. Deluisi
- IV. Data Sets Development
Chairman: Dr. C. Gautier
Vice Chairman: Dr. P. K. Taylor

A complete List of Participants showing primary panel membership (some participants contributed to more than one panel) and addresses is given in Appendix A.

Before the workshop, the panel chairmen prepared position papers as a means of focusing attention on the major issues. These papers, given here in Appendix B, were distributed to the participants and were presented orally at the initial session of the workshop. Also at the initial session, other programs which strongly impact surface radiation budget studies were discussed in invited presentations: the Earth Radiation Budget Experiment (ERBE) by Dr. B. R. Barkstrom, the International Satellite Cloud Climatology Project (ISCCP) by Dr. R. A. Schiffer, and the International Satellite Land-Surface Climatology Project (ISLSCP) by Dr. P. Sellers. Brief descriptions of these programs and other related programs are given in Appendix C.

Prior to the panel discussions, short presentations were given by the participants (see Appendix D) to describe new results on surface radiation. After panel-discussion sessions, the panels prepared reports which form the body of this document.

A list of acronyms used in this document is presented in Appendix E.

SECTION 2

SCIENTIFIC NEEDS AND APPLICATIONS

2.1 INTRODUCTION

Surface radiation budget data have the potential for contributing significantly to improved understanding of the four major components of the climate system: the oceans, the land surface, the cryosphere, and the atmosphere. Radiative fluxes into the ocean surface provide an important boundary forcing for the ocean general circulation. Furthermore, since the radiative fluxes into the ocean surface are significantly modulated by boundary layer parameters (e.g., clouds, atmospheric humidity, and temperatures), SRB may be an important factor in air-sea interactions. With respect to the land surface, the net radiative balance governs the turbulent fluxes of latent and sensible heat from the surface into the atmosphere. Surface radiative fluxes are also needed for studies related to the energy and water balance of plant canopies. For the cryosphere, the pack ice and its interaction with surface temperature and solar radiation provides the so-called ice-albedo feedback which is a vital component governing climate trends on decadal to longer time scales. Finally, the knowledge of SRB together with top-of-the-atmosphere Earth radiation budget data can yield, for the first time, observational estimates of tropospheric radiative heating and cloud radiative forcing.

Thus SRB has a vital role to play in improving our understanding of the global climate and, in what follows, we describe its use separately for each component of the climate system.

In addition to determining SRB, it is also important to determine the parameters that govern the spatial and time mean of SRB and its variations. On time scales ranging from diurnal to interannual, variations in SRB are governed to a large extent by variations in clouds, temperatures, and humidities. For example, in the tropics the noontime absorbed solar radiation can vary from about 1000 Wm^{-2} under clear sky conditions to about 100 Wm^{-2} under overcast conditions. Similarly, interannual variations in solar and longwave fluxes in the tropical oceans can be as large as 50 to 100 Wm^{-2} (e.g., during extreme El Niño events). Availability of SRB data, in conjunction with top-of-the-atmosphere radiation budget (ERB) data, will provide exciting research opportunities in the area of cloud-climate interactions and air-sea interactions.

On time scales ranging from a year to a decade, SRB data (in conjunction with ERB) can be important for elucidating the role of changes in land-surface conditions (e.g., deforestation or desertification) on climate.

On still longer time scales (e.g., decade to a century) climate change due to increases in greenhouse gases and/or aerosols may induce substantial changes in the surface radiation budget. For example, it can be inferred from general circulation model studies that the temperature and humidity increases due to CO_2 doubling can enhance the globally averaged downward longwave fluxes by about $15\text{--}30 \text{ Wm}^{-2}$. In polar regions the downward longwave and absorbed solar fluxes (due to CO_2 doubling) are computed to increase by as much as 50 Wm^{-2} .

The type and accuracy of required measurements depend very crucially on the time scale of interest. For problems that are concerned with interannual to shorter time scales, global distributions of SRB on regional scales are required, whereas, for decadal to longer time scales, surface-based (i.e., local) measurements at several stations distributed around the globe are required (in addition to the global distributions). Furthermore, the longer time scale problems place more stringent accuracy demands than the shorter time scale problems.

Currently, our knowledge of the temporal and spatial variability of SRB is insufficient to objectively specify the required spatial resolution and accuracy for scientific studies. However, we have made a crude estimate in arriving at the numbers specified in this document.

2.2 SPECIFIC SCIENTIFIC APPLICATIONS

2.2.1 Oceans

The radiation budget at the ocean surface is required for several research areas: (1) as a boundary condition for ocean models, (2) to understand the role of radiation in air-sea interactions, (3) to estimate meridional heat transport in the oceans, and (4) to validate coupled ocean-atmosphere models.

Estimates of the requirements for these purposes may be made by taking as examples two major projects of the World Climate Research Program (WCRP): the Tropical Ocean and Global Atmosphere (TOGA) experiment and the World Ocean Circulation Experiment (WOCE). Both are concerned with improving our understanding of and ability to model the interaction between the oceanic and atmospheric general circulations. In the case of TOGA, the emphasis is on the air-sea interaction in the tropics and its effect on climatic variability on the interannual time scale. For WOCE, it is the global circulation of the oceans which is to be studied.

It should be stressed that SRB is only one component of the interaction between the atmosphere and the oceans. Together with the surface sensible and latent heat fluxes it determines the heat input to (or output from) the ocean. However, since the oceanic circulation is also governed by the wind stress and the salinity changes (due to the local difference between precipitation and evaporation), the nature and accuracy required of the SRB data depends in part on these other factors and may vary with geographical location.

The TOGA program commenced on 1 January 1985 and will continue for ten years. It is therefore important that consideration be given to obtaining the SRB retrospectively from the start of 1985.

The only accuracy requirement for radiation data stated in the TOGA Scientific Plan is that for incoming shortwave radiation flux. The requirement is for an accuracy of 10 Wm^{-2} for monthly averages in each 2° latitude by 10° longitude box in the tropical zone (strictly 20°N - 20°S , but taken to be 30°N - 30°S in many studies). It stems mainly from a need to resolve the variations in the net heat flux associated with the El Niño/Southern Oscillation (ENSO) phenomenon, which are of the order 200 Wm^{-2} . Hence an accuracy of 20 Wm^{-2} rms for the net heat flux (averaged as defined above) would thus be appropriate, while an accuracy of 40 Wm^{-2} may still be useful. However, interannual variability in the tropical Atlantic and Indian Oceans is substantially less than in the Pacific.

The net longwave component is thought to be about one-third as large as the shortwave, but its exact value is a matter of current debate as longwave radiation schemes show considerable variations in their predicted downward longwave fluxes at the surface for tropical profiles (WCP 93, 1984). As noted by the TOGA Workshop (WCP 92, 1984), "In situ measurements of surface longwave radiation are rare and difficult to make. As a result, the importance of longwave radiation in the overall determination of net surface flux is not clear. There is insufficient evidence available now to decide whether or not variable longwave radiation will play a critical part in TOGA studies." More work is needed to identify and develop methods for calculating the surface longwave flux from space, but it should be remembered that the absolute accuracy requirements will be essentially the same as for the shortwave radiation. It would thus seem appropriate to define, on a global basis, a benchmark accuracy of 10 Wm^{-2} for the space- and time-averaged surface net-radiation budget (shortwave and longwave combined). Estimates to lower accuracy will still be valuable for research, although the research goals may become more limited if lower precision is achieved.

Although the above accuracy requirements are defined in terms of monthly mean values, for some research projects data on higher time and space resolution are required. In general the surface radiation budget is not likely to be required at a resolution greater than one day or 2° lat. \times 2° long.

Because of the difficulty of obtaining surface longwave fluxes from space, we strongly endorse the recommendation of the TOGA Workshop (WCP 92, 1985) that “a program of in situ measurements of longwave radiation should be established in the tropics.”

Data availability is also an important consideration both in terms of timeliness and ease of access. Surface radiation budget estimates for TOGA should be available within 6 to 18 months of observation. Present planning envisages an Air-Sea Interface Data Centre producing fields of the mean surface fluxes as a non-real-time operational level 3 data product. The SRB data should be made available to this program in level 2 (or level 3 on a standardized grid) form.

Accuracy and data availability requirements for the SRB for WOCE purposes are similar to those for TOGA, and it is expected that WOCE data management will build on that developed for TOGA. However, WOCE requires monthly mean SRB data globally with 5° lat. × 5° long. resolution (2° lat. × 5° long. in the tropics). WOCE is planned to commence in 1990 and continue through 1994.

2.2.2 Land Surface

Measurements of the radiative flux components making up the surface radiation budget of the land surface are required in addition to inferred SRB from satellites for the following purposes:

- (1) **Model verification:** Models of the complex radiative transfer process for a surface covered by a vegetation canopy require validation from local scales up to GCM grid scales.
- (2) **Model boundary conditions:** Except for land covered by snow, the land-surface albedo is not an interactive parameter in GCMs and therefore must be specified as a boundary condition.
- (3) **Surface-atmosphere interaction studies:** The net radiative flux governs the transfer of latent and sensible heat into the atmosphere. Hence, monitoring of the land-surface SRB should help with the investigation of the strength of the surface-atmosphere interactions.

The measurement requirements to meet above objectives are as follows:

Incoming Radiative Fluxes: The amount, spectral composition, and angular distribution of incoming fluxes from 0.3 μm through the thermal IR are required. The *minimum* discrimination should be as follows:

- (1) Amount: 10 Wm^{-2} or 5%.
- (2) Spectral measurements needed in addition to broadband: 0.3–0.4, 0.4–0.7, 0.7–1.1, 0.6–0.7, 0.75–0.85, 10–12 μm .
- (3) Angular distribution: direct/diffuse ratio.

Nadir Reflectances: In view of the land surface’s temporal and spatial variability, monitoring of its radiative properties on large scales is only feasible using satellite-borne viewing sensors. These should make observations within or close to the chlorophyll “jump,” i.e., 0.6–30.7 μm and 0.75–0.85 μm . Measurements of the reflectance at these wavelengths are needed at the surface for a variety of vegetation types.

Albedo/BRDF: Surface measurements of the hemispherical albedo and the bidirectional reflectance distribution functions (BRDFs) of various surfaces under different conditions at several wavelengths should be done regularly. These will be used to translate the satellite directional reflectances to hemispherical albedos for radiative transfer modeling.

Surface Temperature: Measurements of ground temperature are not only useful for determining the net longwave balance but also may be used to infer the partitioning of the net radiation into the surface heat fluxes via soil-plant-atmosphere models. The same methodology may also be used to obtain an indication of the soil-moisture content.

Spatial and Temporal Resolution

The surface and atmospheric measurements will be constrained by resources and instrument design. Clearly, temporal sampling must be carried out at monthly or more frequent intervals to take account of seasonal variations. The monitoring (satellite-based) effort should place emphasis on the temporal variability rather than trying to pursue a fine spatial resolution. For climate research, AVHRR or GOES scale measurements (< 10 km) aggregated and statistically analyzed on the GCM grid scale are adequate.

Other Considerations

Other considerations result from the following facts:

- (1) Satellite remote sensing represents the only practical way of monitoring the land-surface radiation budget.
- (2) There is ambiguity concerning the differential contributions of the land surface and aerosols to the clear sky TOA radiances.

It is imperative that some means of quantifying the effects of aerosols, if necessary via a global scale measurement effort, be provided in order to achieve the preceding objectives. The costs of such an effort should be scaled against the costs of the satellite observing systems.

2.2.3 The Cryosphere

The net radiation is usually the largest term in the energy budget of snow surfaces. The latent and sensible heat fluxes are usually small (and often directed from the atmosphere to the surface). The net radiation therefore controls the timing and rate of snow melt. It is needed for regional studies of snow as well as for climate modeling.

Snow cover is thought to cause a positive feedback on climatic change, both because its albedo is higher than that of the underlying ground or sea ice and also because its albedo decreases as the snow temperature increases. Surface radiation budget measurements, especially in regions which are seasonally snow covered, are needed, together with the monitoring of snow and ice area, to determine whether this feedback is being modeled properly in climate models.

The Antarctic surface is almost all far below freezing throughout the year, so the snow albedo probably does not vary much. However, the snow surface of the Greenland ice sheet undergoes some melting over about 70% of its area. The most variable parts of the cryosphere, and therefore the most sensitive to climatic change, are the seasonal snow and sea ice. The areal average albedo of Arctic sea ice in summer is controlled by the fractional coverage of melt puddles. Monitoring of either puddle coverage or albedo would be useful, but is difficult to do from satellites because of the persistent stratus cloud cover during the melt season. The Antarctic sea ice covers an area as large as South America at its maximum extent, but melts completely every year over most of its area. Observations at the surface are very scarce except near the continent. However, there are suggestions that Antarctic sea ice has higher albedo than the Arctic, and very few puddles. This is also a very cloudy region.

Snow and sea-ice areas are now being monitored, approximately weekly, using a combination of surface observations, satellite visible reflectance, and satellite microwave emission. This monitoring should be continued and improved.

Over snow, the net radiation budget is often a small difference of 2 or 4 large terms involving up and down solar as well as longwave radiation. The net radiation is probably needed to 10 Wm⁻² accuracy or better (for monthly average, 250 km resolution). It may be difficult to extrapolate from visible-channel (0.5–0.7 μm) albedo to total albedo because most of the variability in snow albedo

occurs at longer wavelengths. It is therefore important to continue the radiation-monitoring work under way at Arctic and Antarctic surfaces. Satellite-inferred SRB checked at these sites could extend SRB estimates to wider geographical regions. Because polar snow surfaces are more homogeneous (horizontally) than are land surfaces, point measurements at the surface may be representative of large areas.

2.2.4 The Atmosphere

The difference between top-of-the-atmosphere Earth radiation budget (ERB) and SRB yields the net radiative heating (cooling) of the atmosphere. On a global average basis the divergence of radiative (solar and longwave) energy from the troposphere is about 150 Wm^{-2} , which is balanced by the turbulent fluxes of sensible and latent heat from the surface.

Recent diagnostic and general circulation model studies (e.g., see the position paper for Panel 1) suggest that spatial (i.e., meridional and longitudinal) and temporal variations in the tropospheric radiative flux divergence play an important role in the tropospheric general circulation. For example: model studies indicate that cloud radiative forcing contributes a flux convergence of the order of $50\text{--}100 \text{ Wm}^{-2}$ in the monsoon regions; GCM studies also reveal that cloud radiation forcing enhances the eddy kinetic energy in the troposphere; diagnostic studies employing observed cloudiness in conjunction with linearized dynamical models indicate that the longitudinal asymmetries in radiative heating contribute significantly to planetary scale waves; and GCM studies also suggest that cirrus radiative heating can play an important role in governing the tropical thermal structure and the strength of the tropospheric jet. Furthermore, a number of GCM studies are currently exploring the role of cloud radiative processes in medium range forecasting.

The role of troposphere radiative forcing and its interactions with the atmospheric general circulation is an important area of research and there are virtually no data to verify the existing conclusions of model studies.

In order to make further progress, SRB data are needed in conjunction with ERB. It is crucial to make estimates for clear skies separately. As explained in the appendix (see the position paper), from estimates of SRB and ERB separately for clear skies and cloudy skies, we can infer the role of cloud radiative forcing of the general circulation.

The data are needed on regional scales (approx. $2.5^\circ \times 2.5^\circ$). The accuracies of SRB and ERB should be such that the tropospheric radiative forcing can be estimated to about 25 Wm^{-2} .

The effects of different types of clouds on the downward longwave radiation at the surface could be investigated by comparing a climatology of observed cloud type amounts and base heights with measurements of longwave fluxes under different specific cloud types.

2.2.5 Model Verification

The surface radiation budget is useful for providing the forcing of ocean circulation models, but if obtained accurately from measurements it is also of great use in verifying the radiative parameterizations of atmospheric general circulation models. This verification can be carried out through knowledge of the individual components of the SRB and also the ancillary data that must be used in obtaining the SRB.

Modelers are particularly keen on obtaining data on the radiation components from the First ISCCP Regional Experiment (FIRE), which will provide the SRB under cloudy conditions at points in a region of GCM grid scale, along with meteorological parameters that will have been measured in the same experiment region. Models use mean properties of the layer at scales of several hundred kilometers to parameterize the radiative properties of the layer, although, strictly speaking, radiative

transfer models can only be used to compute point properties. Since the study of the relationship between point source measurements and spatial averages is a crucial element of any SRB project, the modelers will obtain data crucial for testing their parameterizations.

A field program to measure clear sky longwave radiances could resolve some of the uncertainty in radiation modeling that was evident after ICRCCM. One heartening result of ICRCCM was that some broadband models that are used in GCMs were found to be computing clear sky fluxes very close to line-by-line (LBL) calculations. A major reason for this agreement was that the broadband models were tuned to LBL computations. Therefore, it is imperative to know how closely LBL results represent nature under controlled clear sky conditions.

Finally, the overall SRB of the model and derived SRB based on satellite and surface observations can be compared in a manner similar to the current programs that compare TOA radiation fields of models and satellites. Just as TOA fields can be used to validate cloud generation algorithms of GCMs to some extent, SRB data can give correlative information regarding cloud bases. Several GCMs now have diurnal cycles with internally generated clouds including boundary layer cloudiness. These low-level clouds are difficult to validate from TOA results but their contribution to SRB creates a large signal that can delineate the extent and occurrence of these clouds. A word of caution here is that SRB algorithms relying solely on TOA observations will not provide any additional information. Therefore, surface-based observations of cloud base heights will be needed for validation of cloud effects on the surface radiation budget.

2.2.6 Long-Term Climate Trends

There are two outstanding issues in which radiation data can play a central role.

The first concerns the role of cloud feedback in governing climate sensitivity. The ISCCP-type cloud data are aimed at improving parameterization of clouds in climate models. However, we need observed estimates of the role of clouds in modulating the radiative forcing due to natural variations (e.g., volcanic aerosols and solar variation) or due to anthropogenic influences (e.g., trace gases and deforestation). For this purpose, we strongly recommend long-term monitoring of the TOA albedo to a high degree of accuracy ($\sim 0.1\%$) on larger scales (e.g., continental to ocean basin).

In conjunction, the clear sky surface albedo of the planet (and its trend) should be determined simultaneously. These data, in conjunction with SRB, would provide information concerning cloud feedback, ice-albedo feedback, and the radiative forcing due to land-surface changes such as desertification.

The second issue concerns verification of feedbacks involving ice-albedo and H_2O -greenhouse effects. As mentioned earlier, these feedbacks induce (in model calculations) large changes in SRB. It would be important to monitor the downward longwave flux and absorbed solar fluxes at selected stations in Arctic, Antarctic, tropical, and midlatitude regions. The accuracy of the measurements should be such that trends of the order of $5\text{--}10\text{ Wm}^{-2}$ per decade are detectable. In addition to broadband measurements, we also recommend making surface irradiance measurements in narrow spectral intervals ($\sim 10\text{ cm}^{-1}$ for longwave; $0.05\ \mu\text{m}$ in shortwave) to help sort out flux changes due to radiative forcing (e.g., trace gas increase or aerosol changes) from those resulting from the response of climate (e.g., changes in H_2O , temperature, or clouds).

Aerosols probably have more effect on the radiation budget at the surface than they do at TOA. The reduction of the clear sky solar irradiance at the surface due to tropospheric aerosol has been estimated at 7% on average for the eastern U.S. and about 1% on global average. Measurement records of turbidity and the ratio of direct to diffuse solar radiation at remote sites, such as Mauna Loa, are important for the establishment of aerosol background loading and should definitely be continued in order to establish any possible relationship to surface radiation trends. Without these

measurements it would be impossible to identify the cause of changes in surface solar radiation, whether from cloud changes, variations in the solar constant, or changes in aerosols or other species.

2.3 CONCLUSIONS

2.3.1 Summary of SRB Uses

OCEANS	<ul style="list-style-type: none"> (1) Diagnostic uses <ul style="list-style-type: none"> (a) Understanding the role of radiation in air-sea interactions (e.g., TOGA) (b) Inferring meridional heat transport (2) Boundary condition for ocean models (3) Validation of coupled ocean-atmosphere models
LAND SURFACE	<ul style="list-style-type: none"> (1) Validation of radiative transfer models for vegetated canopies (2) Specification of albedo boundary conditions for GCMs (3) Surface-atmosphere interaction studies (reflectance, Bowen ratio, soil moisture) (4) Aerosols (TOA radiance ambiguity)
CRYOSPHERE	<ul style="list-style-type: none"> (1) Improved parameterization of snow-ice albedo feedback (2) Relate long-term trends in snow-ice cover to radiation flux changes
ATMOSPHERE	<ul style="list-style-type: none"> (1) Role of radiative heating in the general circulation (2) Cloud radiative forcing (3) Parameterization of sub-grid-scale inhomogeneities
MODEL VERIFICATION	<ul style="list-style-type: none"> (1) Validation of radiative parameterizations for GCMs (2) Validation of cloud generation algorithms of GCMs
LONG-TERM CLIMATE TRENDS	<p>To understand and determine trends in the following quantities:</p> <ul style="list-style-type: none"> (1) Surface albedo (deserts, snow, and ice) (2) TOA broadband albedo (3) Solar irradiance (4) Surface downward LW and SW (measured at remote stations) (5) Direct-to-total SW flux ratio (6) Atmospheric transparency

2.3.2 Requirements

The requirements specified in the text above for model studies and interannual variability are summarized here.

Region	Resolution		Accuracy			
	Space	Time	Net SW Wm ⁻²	Albedo	Net LW Wm ⁻²	Net Wm ⁻²
Ocean						
Tropical	2° × 10°	month				10
Extratropical	5° × 5°	month				10
Land	250 km	month	10	0.05	10	
Cryosphere	250 km	month		<0.05		<10
Atmosphere	250 km	month				<25

2.3.3 Recommendations

In summary, our panel strongly recommends initiation of efforts aimed at determining global and regional distributions of shortwave and longwave fluxes at the surface. Specific recommendations of the panel are listed below.

- (1) We view the SRB from satellite measurements as a research problem. We recommend modeling and experimental studies to interpret the information content of satellite-measured radiances. In particular, the narrowband radiances in the visible by themselves have no information about tropospheric absorption. However, for some uses (e.g., oceanographic) narrowband radiances may be adequate for estimating insolation and absorption of solar radiation at the surface.
- (2) All components of the SRB should be determined: upward and downward shortwave and longwave fluxes along with SW albedo, LW emissivity, and surface temperature.
- (3) Specific measurements of high absolute accuracy are needed for model parameterizations:
 - a. spectral albedo of snow, sea ice, and soil, as affected respectively by grain size, melt puddles, and wetness.
 - b. longwave radiance field experiment for clear sky.
 - c. effect of sub-grid-scale inhomogeneities (especially clouds) on large-scale shortwave fluxes.
- (4) We give very high priority to broadband ERB measurements. Without ERB, it is very difficult to scientifically interpret SRB data. In connection with this, research is needed to understand the variation with wavelength of the optical properties of clouds.
- (5) We recommend research with both narrowband and broadband data to infer SRB fluxes. In particular, broadband fluxes contain information about atmospheric absorption.

SECTION 3

OBSERVATIONS AND ANALYSIS

3.1 INTRODUCTION

Three general approaches have been used to observe or estimate the components of the surface radiation budget:

- (1) Estimates based primarily on measured *spectral radiances* from satellites. These provide the advantage of global coverage with sufficient spatial and temporal detail. However, they suffer from the facts that they are not based on observations covering the entire spectrum and that they have to be corrected for atmospheric effects.
- (2) Estimates based on radiative transfer calculations. These require input data describing the structure of the overlying atmosphere (i.e., moisture and temperature profiles, cloud conditions, etc.) and would not be feasible for the entire globe unless such input information were adequately derived from satellite data.
- (3) Observations from instruments at the surface. There is a rather sparse network of surface stations that measure solar radiation and, in some cases, other components of the surface radiation budget. In the context of climate applications, such observations are required for long-term monitoring of SRB at selected sites and for validating SRB determinations from satellites.

The present status, major questions, and future development of approaches (1) and (2) are summarized in this section; approach (3) is discussed in section 4.

To illustrate possible magnitudes of all four components of the radiation budget at the Earth's surface an example is given in Figure 1 (from W. J. Shuttleworth et al., 1984). These measurements were obtained above the Amazonian rain forest. The upward and downward fluxes of infrared thermal radiation reach values of up to 460 Wm^{-2} . The net infrared radiation energy loss of the forest is about $45\text{--}50 \text{ Wm}^{-2}$ and is rather invariable. The total net radiative gain of the forest can be compensated only by other heat fluxes: latent and sensible heat exchange. Measurements of similar magnitude have also been obtained over the tropical oceans (e.g., during GATE). Over most continental surfaces at higher latitudes and over deserts, the net radiation undergoes much larger variations, even with changes of sign.

3.2 STATE OF KNOWLEDGE

3.2.1 Satellite Radiance Methods

SRB estimates from satellites generally make use of the information content of imaging data from operational meteorological satellites. They are retrieved on the basis of a variable set of assumptions and other a priori information concerning the transmittance of the clouds and atmosphere for solar radiation and near-surface temperatures and moisture as well as clouds for thermal radiation. A recent review of the methods has been given by Raschke (1985).

3.2.1.1 *Incident solar radiation*

Techniques for estimating the solar radiation incident at the surface, i.e., the global radiation, have been developed in the past years by several authors (e.g., Major, 1976; Hay and Hanson, 1978; Tarpley, 1979; Gautier et al., 1980; Möser and Raschke, 1984; Pinker and Ewing, 1985; and further

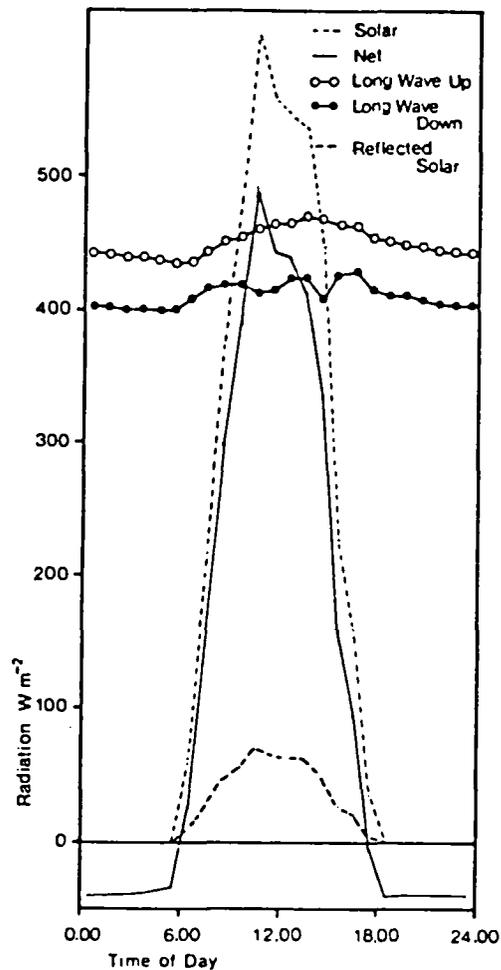


Figure 1. The mean value of radiation components above Amazonian rain forest for six days of continuous data (Shuttleworth et al., 1984, Figure 2., ©Royal Meteorological Society).

sources quoted in these articles). There are two general categories of methods. One uses empirical regressions between simultaneous and collocated satellite radiances and ground-based pyranometer data. In the second approach the information contained in the satellite radiances is interpreted in terms of scattering, reflection, and absorption parameters which are subsequently used in radiative transfer model calculations. The physical basis of both methods is that the major modulator of surface insolation is cloudiness, which is also the major determinant of reflected solar radiation. An intercomparison of some representative samples of both types of methods has recently been made by Raphael and Hay (1984).

In practice the "satellite radiances" which are used as the prime data source are obtained with imaging radiometers of the operational geostationary or polar orbiting satellites. Spectral sensitivity is primarily located in the visible and near infrared portions, where the atmosphere and clouds absorb only small amounts of the incident solar radiation. The signals of the clear atmosphere are influenced principally by absorption due to ozone and water vapor, by Rayleigh scattering, and by rather variable scattering and absorption by aerosols. The clouds affect the signal due to their optical thickness and the fractional coverage within the field of view.

Most authors have used satellite data with the highest possible resolution. Such large data sets might be difficult to deal with in an operational implementation. Therefore, an attempt has been made by Gratzki (1985) to derive daily sums of the global irradiances at ground from Meteosat data which have been sampled according to the B2-scheme of ISCCP (30 km spatially sampled and 3 hourly sampled data). Comparison with observations of 187 stations located in Europe and Africa yielded errors of 18% for daily totals and 10% for monthly mean values.

Experience to date in estimating insolation from satellite data leads to several conclusions. All algorithms that have been developed have produced results with errors of 10–15% in daily estimates and about 5–10% in long-term means of the daily estimates. These error limits can partly be explained by the fact that the field of view of pyranometers used for validation does not agree with that of the satellite radiometer, nor is the navigation of satellite data accurate enough in all cases to allow for exact intercomparisons. Attempts to use thermal infrared data and information on cloud altitude have not produced significantly greater accuracy. It seems safe to conclude that current algorithms are making use of most of the information available in the operational satellite data.

For most of the world, hourly or 3 hourly (ISCCP-B3) geostationary data could be adequate for insolation estimates. In some satellite models, spatial averages of instantaneous satellite observations are compared with time averaged point (pyranometer) measurements at the surface. The frequency of the satellite observations is then related to the horizontal resolution by the expression

$$x \sim ut$$

where x is the horizontal resolution of the estimates, u is the mean speed of cloud features, and t is the interval between satellite observations. If $u = 50$ km/hour, then the appropriate resolution of insolation estimates is 50 km for hourly data and 150 km for 3 hourly data. In other models daily sums are compared, whereby a minimum of spatial averaging is employed.

The oceans are probably the least complex area for estimating insolation because of their uniform dark surface, which provides a good contrast to clouds. The major complicating factor is sunglint, which for certain hours will reduce or eliminate the cloud and surface contrast. Several authors ignore such data. Accuracies of 30-day means of daily total insolation should be at least as good as that for continental areas, i.e., within the 10–20 Wm^{-2} range or about 5–10%. For non-tropical ocean areas where sunglint is not a problem accuracies should be slightly higher.

For land areas monthly mean accuracies of 10–20 Wm^{-2} or 5–10% appear to be feasible. This level of accuracy has been achieved for several models at different locations. Determinations of incident solar radiation over polar regions from satellite data have not been attempted.

All algorithms are expected to contain biases introduced by calibration, site specificity, errors in physical parameters, and other effects. More ground observations are required to detect biases and subsequently correct the estimates. *There is an urgent need to establish ground truth over the oceans.*

Routine production of insolation estimates has been started in the U.S. with GOES data, in Europe (France and Germany) with data from Meteosat, and in Australia with GMS data. The time series of U.S. insolation estimates dates back to February 1983, and provides a spatial resolution of about 1° by latitude and longitude. A project to produce insolation estimates for the tropical Pacific has been proposed by Scripps Institution of Oceanography (Gautier, 1985, private communication).

3.2.1.2 Surface albedo

Routine procedures to derive the surface albedo on a global or even a regional scale from satellites are not presently available. Only experimental studies have been conducted thus far and they are heterogeneous with respect to the spectral responses of the instruments, the spatial and temporal scales of the observations used, and the methodologies applied (Pinker, 1985a). No systematic error analysis has yet been published.

Relevant satellite sensors include the same imaging sensors whose data are used to determine cloud fields and the downward solar radiation at ground. In addition, the surface albedo has been derived from Landsat (e.g., Otterman and Fraser, 1976), and from Nimbus 2, 3, 6, and 7 (Preuss and Geleyn, 1980). The current ERBS and NOAA satellites of the ERBE project will provide more data for this purpose. There are important limitations to all these data sources due to deficiencies in the calibration; in the different spectral filter functions and wavelength-ranges; and in the spatial, temporal, and angular sampling. In addition, the results are biased since they can be obtained from clear sky measurements only.

Basically, one attempts to find a clear scene. To derive the surface albedo from such clear sky observations, they must be corrected for atmospheric gases and aerosols as well as undetectable contributions from subscale cloudiness. Moreover, since most of the satellite observations are narrow-band measurements, the spectral reflection properties of the scene on Earth must be taken into account. A relevant procedure might require a data library on vegetation coverage and its seasonal changes and other properties affecting the spectral reflection characteristics of the surface.

It may be feasible to map the surface albedo using part of the same data sets (e.g., ISCCP-B3-solar channels, clear sky radiances) that could be used for insolation estimates. For monitoring local albedo variations, Landsat observations would be appropriate.

3.2.1.3 *Downward atmospheric radiation at surface*

Several research groups have tried to estimate the downward atmospheric radiation from satellite radiances. Methods include either direct use of vertical sounder data (Darnell et al., 1983; Morcrette and Deschamps, 1983; and Smith and Woolf, 1983) or analyzed air temperature fields (operational grid point analyses) together with satellite-based information on clouds, their height ranges, and possible thicknesses (P. Schmetz et al., 1985). Smith and Vonder Haar (1980) and Atwater and Ball (1981) carefully analyzed the GATE data sets. Quoted rms differences with direct measurements range between 5% and 10% ($20\text{--}40 \text{ Wm}^{-2}$).

Since the downward atmospheric radiation at ground levels originates predominantly from thermal emissions in the lowest atmospheric layers (up to 1000 meters) and from cloud bases (in regions where atmospheric water vapor amounts are small), uncertainties in atmospheric temperature and moisture, as well as cloud base heights and emittance, are the major error sources (Fung et al., 1984). The lower atmospheric temperature and moisture cannot be determined from satellite sounding data to accuracies of better than 2.5 K and 20% to 30%, respectively. P. Schmetz (1984) made an error estimate study for a few model atmospheres and showed that overall uncertainties (rms) of $10\text{--}15 \text{ Wm}^{-2}$ are possible, when the temperature is uncertain to $\pm 1.5 \text{ K}$, the moisture $\pm 20\%$, and cloud base altitudes by 500 to 1000 m, depending on cloud type. P. Schmetz et al. (1985) used analyzed grid point temperatures of the ALPEX area, where images of Meteosat provided information on clouds.

Darnell et al. (1983) developed a method for determining downward atmospheric radiation at the surface based on the use of a radiative transfer model and operational meteorological sounding data from the NOAA-TOVS instrument. These data sets provide near-surface water vapor and temperature profiles as well as cloud fraction and cloud top pressure. An assumption for cloud thickness was employed to establish the required cloud base height data. Using this technique, flux differences of 10 Wm^{-2} were obtained between satellite derived fluxes and ground observations for a midlatitude, continental site and a one month averaging period.

No systematic error analysis has yet been made covering all climate regions of the globe and considering integration over time periods ranging from minutes to a month. Such studies are urgently needed.

3.2.1.4 *Surface temperature and emittance*

Sea surface temperatures are routinely obtained from satellites; methods for land-surface temperatures are still in an exploratory stage. The measurements are primarily being made with imaging radiometers sensitive to radiation in the atmospheric infrared windows. Here the contribution of emission from the cloud-free atmosphere is relatively small, although it can be important in humid tropical regions (e.g., emission by dimers and water vapor line wings). Recently, Susskind et al. (1984) used the infrared and microwave measurements of the TOVS for estimates of global surface temperatures for all sky conditions.

Validations of sea surface temperature indicate accuracies of 0.5 to 1.5 K. Larger uncertainties in surface temperature determinations will occur over land, where screening for clouds is more difficult, the emissivities may depart from unity, and the spatial variability is great. However, no ground truth is yet available for the preliminary results on this quantity. While the microwave region may be used to penetrate clouds, the surface emittance is much smaller and more variable than in the infrared. Because of the spatial variability of land-surface emission, the verification of satellite determinations requires either a network of surface observations or aircraft observations to integrate over several satellite pixels.

3.2.2 SRB from Radiative Transfer Calculations

3.2.2.1 *Introduction*

Although treated here as a separate topic, radiative transfer calculations are required in all procedures for transforming top-of-atmosphere radiance observations to SRB components, except for those based on pure empirical regression techniques. There is a hierarchy of different modeling approaches that vary in complexity in their attempt to model both the solar and infrared radiation at the surface. Through necessity these models are based on the assumption that the atmosphere and surface are horizontally uniform and, for the most part, they provide only broadband solar fluxes incident and reflected at the surface and infrared fluxes emitted by the surface.

Chou (1985) has calculated monthly surface radiative fluxes for the tropical Pacific region using detailed radiation models and climatological data for surface, atmospheric, and cloud inputs. Based upon the expected uncertainties in the input data, the rms error in the calculated net surface radiation was estimated to be approximately 15 Wm^{-2} , with the largest contributions from cloud cover and humidity.

Accuracies of $\pm 10\text{--}20 \text{ Wm}^{-2}$ are believed to be typical of model calculated monthly mean solar flux and downward longwave radiation at the surface. In the tropics the large overburden of atmospheric moisture produces an insensitivity of the longwave flux to the cloud parameters. However, the errors in flux calculated for regions poleward of the tropics are very sensitive to the emission from cloud bases. While this error can be reduced substantially by tuning models to site specific data, there is still the problem of applicability of these tuned models to other regions.

A systematic study of radiative transfer codes to be used in climate models has been initiated by the Radiation Commission of IAMAP (WCP 93, 1984)—the Intercomparison of Radiation Codes in Climate Models (ICRCCM).

3.2.2.2 *Input data*

(A) Input Data for Solar Radiation

Input data for the models vary in complexity with the sophistication of the particular model. These data are sometimes prescribed (as in the case of aerosols) or derived from satellite

measurements or from other sources, such as operational meteorological analyses. The following were identified as important data for models (although not all incorporate these).

- (1) Surface albedo (function of wavelength and zenith angle in some models)
- (2) The vertical distribution of temperature
- (3) The vertical distribution of water vapor
- (4) The vertical distribution of ozone (and other trace gases)
- (5) Cloud parameters
 - morphology (type, height, fractional cover, etc.)
 - phase (water/ice)
 - cloud optical thickness or liquid water content
- (6) Solar zenith angle
- (7) Aerosol: This parameter is usually prescribed using some model of aerosol optical properties

(B) Input Data Parameters for Infrared Radiation

In addition to the above data, the following are required of most IR models.

- (1) Surface emittance
- (2) Surface temperature
- (3) Cloud base temperature
- (4) Cloud base pressure or altitude
- (5) Cloud emittance

3.2.2.3 *Limitations and potential improvements*

To date, the ability of models to calculate solar and infrared fluxes at the surface and their variability is limited to the appropriate specification of input parameters and their variability. Model calculations have been performed for a variety of scales varying from the synoptic to the regional scale on which validation is possible.

In a typical GCM grid of 250×250 km and a time interval of about 4 hours, the input data to radiative transfer schemes vary with space and time. Surface radiation components computed from a set of mean input data within the grid and time interval will be different from the means of surface radiation computed with the full spatial and temporal resolution. Our current knowledge of the effect of these spatial and temporal variations is rather poor. Presumably, the effects should depend strongly with climatic regions and seasons.

Longwave radiative transfer models, when applied to identical data sets, have shown considerable deviations in their results. Therefore, during recent years an intercomparison has begun to identify error sources in these codes, which are used in climate and circulation models. This project is the first phase of the ICRCCM study (WCP 93, 1984). Emphasis is being placed on the continuum absorption of water vapor in the window region. Now newer laboratory data of the continuum absorption are available and the effects on surface radiation are being reassessed.

One of the primary uncertainties in shortwave radiation transfer modeling is the assumption of plane-parallel cloud layers. Extensive studies of radiative transfer in cases of broken cloudiness have been performed and the effects found to be significant. Some efforts are being directed to the parameterization of solar radiative transfer in broken clouds for use in climate models. Results of these parameterizations can be used in the surface radiation calculations.

Another planned effort is the improvement of the input data required for radiative transfer calculations. Some of the approaches to improve the input data are:

- (1) Remote sensing of surface albedo individually in the spectral regions above and below $0.7 \mu\text{m}$;
- (2) Estimation of cloud base from the information on cloud type and height as inferred from satellite measurements (ISCCP); and
- (3) Improvement of column water vapor content using satellite measurements in the microwave channels.

Major gaps exist in the knowledge on input data. These are in particular:

- (1) Temperature and moisture fields within the planetary boundary layer
- (2) Cloud bottom altitudes and emittances
- (3) Aerosols in the troposphere (global aerosol climatology)
- (4) Specification of clouds and their optical properties—especially for cirrus
- (5) Surface albedos
- (6) Natural inhomogeneities of the cloud and surface parameters

Sensitivity analyses, showing the effects of input data errors on estimated fluxes, are badly needed. Although some sensitivity and error analysis has been done, much more is needed to cover the full set of parameters and the differing climatological conditions over the globe. Parameters which should be investigated are: surface albedo; surface emissivity; cloud emissivity; surface temperature, profile values of atmospheric temperature, water vapor, and ozone; fractional cloud cover; cloud base height; and cloud optical depth.

3.2.2.4 Conclusions

For the modeling of the surface radiation budget the following conclusions can be drawn:

- (1) Modeling the monthly solar components of the SRB seems to be possible within $10\text{--}20 \text{ Wm}^{-2}$.
- (2) One of the major limitations of surface radiation budget models is the inadequate specification of the input parameters and their variability.
- (3) Modeling the longwave flux is plagued by uncertainties on the continuum absorption of water vapor in the window region and in the input parameters, particularly near surface temperature and water vapor and cloud base temperatures.
- (4) Parameterizations of solar radiation transfer in broken clouds must be developed and verified to remove the assumption of plane-parallel cloud layers.
- (5) A major problem of modeling the surface radiation budget is the inability of the model to incorporate the effects of the natural inhomogeneity of clouds and the land surfaces.

3.3 RECOMMENDATIONS

In view of the requirements of the TOGA project and the success of several algorithms for determining surface insolation from the visible observations of geostationary satellites, we recommend the initiation of a project to determine insolation over the tropical oceans from satellite observations. As a first step we recommend that a pilot study be conducted to compare existing algorithms against each other and against ground truth. The global, 30 km spatially sampled, and 3 hourly sampled data sets available in the ISCCP archive appear to be suitable for this purpose. These satellite radiance

observations, together with the ancillary data on temperature, humidity, snow, and ice cover provide a unique data set for research on SRB determinations from satellite observations and from radiative transfer calculations. Initial priority should be given to insolation; however, we recommend that the pilot study also include evaluation of the other components of the surface radiation budget. Planning of such a pilot study must include provisions for adequate ground truth.

Once an insolation algorithm has been selected, it could be implemented operationally by a surface radiation budget center (SRBC) that could be set up under the auspices of the ISCCP Working Group on Data Management.

SECTION 4

CALIBRATION AND VALIDATION

4.1 INTRODUCTION

This chapter considers the validation of surface radiation budget components derived from satellite data by the use of ground-based or aircraft measurements and the calibration of instruments used for all of these measurements. The validation process is one of demonstrating the accuracy of the satellite-derived radiance or radiation flux at the surface. Therefore the satellite measurements must be independently calibrated before they can be validated by ground or aircraft data. Section 4.2 discusses calibration, including calibration of both satellite and ground-based sensors. Section 4.3 discusses both the present validation procedures, which use the existing surface network, and planned validation by new ground-based and aircraft measurements.

In this context validation is defined as the attempt to determine the reliability, consistency, and/or accuracy of data by:

- (1) Plausibility tests
- (2) Simple physical constraints
- (3) Forcing to a known or assumed integral value
- (4) Comparison to in situ measurements
- (5) Comparison to radiative transfer modeling
- (6) Comparison to parameterization via easily accessible quantities.

4.2 CALIBRATION

4.2.1 Onboard Calibration of Satellite Radiometers

4.2.1.1 *Current satellite instruments*

Most of the satellite instruments to be used in determining surface radiation budget components are very incompletely characterized and calibrated, with the exception of those on the Earth Radiation Budget Experiment. This experiment is the only one which provides absolute calibration traceability for Earth-viewing data. Accordingly, it is the only satellite source of Earth-viewing data which can be used for calibration transfer. ERBE has had the most complete characterization of spectral, angular, and thermal response, as well as an absolute calibration that is carried into orbit.

Thus, any program of satellite measurements which aims at production of data in absolute units must rely on transfer of calibration from the broadband measurements of the ERBE sensors. Such calibration traceability is only assured if the transfer is made from nearly simultaneous measurements in which the line of sight is essentially the same with respect to a given ground target. Even here, some care is required in the satellite navigation and overlap of instrument fields of view.

Of particular concern is the conversion from narrowband measurements to the broadband measurements made by the radiation budget instruments. Even though ERBE makes broadband measurements, the data processing includes scene, latitude, and angular dependent corrections for the optical train transmission of the instruments. The regressions from narrowband to broadband, which are used for operational satellite data, presently do not include corrections for spectral variabilities due to a number of important effects such as water vapor changes with geographical position, scene reflectance (vegetation, desert, snow, etc.), and solar zenith angle. Although the

operational regressions may produce reasonable appearances in global maps, their use in detailed intercomparisons must be of concern, particularly for the limited regions normally used for validation.

Accordingly, for validation purposes, it is recommended that ERBE observations within one orbit of the desired intercomparisons be used in regressions against any narrowband measurements. These observations should also be made with viewing geometries as close as possible to those that will be used in deriving the surface radiation budget.

In more routine calibration transfers, the ERBE measurements should be used with viewing geometries as close as possible to the views from the satellite to which the transfer is to be made. Research into the number of distinct scene characterizations and angular bins that are required to achieve satisfactory reductions in uncertainty is also advisable. This imposes particular burdens on the GOES data, for which the gains of each of the eight telescopes are subject to daily changes to obtain satisfactory image quality. It is not known whether or not the GOES instruments suffer from serious changes in spectral response or from response changes caused by thermal cycle variations associated with solar and Earth energy input around an orbit. Also, there are analogous problems with Meteosat in terms of the fine adjustment of gain on the channels.

4.2.1.2 *Future satellite instruments*

Because the parameters desired for climate research must be measured over times longer than the life of individual satellites or satellite projects, the only way to ensure that observed trends are the result of changes on Earth and not in the instruments is to provide absolute calibration traceability and characterization of the spectral and angular response of the instruments. Thus, in-flight calibration capabilities are required for any future instruments intended for climate data use. Furthermore, there must be sufficient overlap of satellite observing systems such that the response of an early system can be checked against that of the following one by direct intercomparison.

Most satellite radiometers convert radiation to heat. Thus, they are sensitive to extraneous heat flows induced by solar or Earth radiation. The fundamental principle of good instrument design is then the active control of instrument temperature. The next step in assuring acceptable radiometric performance in orbit is the construction of detailed analytic models of instrument radiometric performance, so that the relationship between the incident radiation and the signal sent to the ground is clearly described. An adequate model will provide an equation for data reduction, as well as an estimate of the sensitivity of the instrument response to extraneous variables, which can be used both to diagnose in-flight operation and to provide error analysis input.

After a rigorous model has been developed, it must be shown that the model's description of instrument behavior corresponds to that of the actual hardware. In addition, spectral response and point spread function must be measured and documented. This also applies to calibration sources. It is conventional to think of in-flight calibration primarily in terms of sources of radiation, such as the Sun or blackbodies. However, it is also important to find as many possibilities for detailed checks of instrument performance with housekeeping data and for redundancies in calibration capabilities. Redundancy of calibration sources and capabilities for intercomparison of different detectors is highly desirable. Detectors can observe blackbodies, the Sun, space, and an incandescent light. This multiple source redundancy allows checking of instrument response calibrations from one source, and markedly improves the credibility of the entire calibration process. Similarly, the ability to simultaneously observe the same footprint with different sensors adds markedly to the possibilities for improving the credibility of a calibration.

It is possible that in the long run the best approach to absolute calibration is to provide a facility in orbit devoted largely to radiometric calibration. Such a facility could be placed on the Space Station, and could provide numerous possibilities for broadband and spectral calibration traceable both to the temperature scale and to the solar output.

4.2.2 Aircraft Calibration of Satellite Radiometers

Ideally, one would like to calibrate a satellite radiometer by putting a primary calibration source alongside it in space. Lacking onboard calibration, the next best solution would be to look at the same scene with an identical, recently calibrated sensor. Since it has been impractical to episodically put such an identical sensor in space (although the Space Shuttle-Space Station complex may change that), the next best platform is a high-flying aircraft. Theory or empiricism can be used to correct for the atmosphere above the aircraft. If it flies well above cirrus clouds the corrections are a few percent at most, and so model errors would have little impact.

Such aircraft calibrations are relatively recent. Hovis et al. (1985) calibrated the Coastal Zone Color Scanner on Nimbus 7 this way, and found drifts up to 25%. But this was only attempted when it was obvious that the data had degraded. This highlights the problem: what should be a routine, episodic activity is instead only undertaken when catastrophic degradation is in evidence. Compared with the \$100M cost of satellites, a dedicated, ongoing aircraft calibration program would cost very little if backup copies of the satellite instruments were flown.

The disadvantages of an aircraft calibration are: first, the timing must be precise; second, only one pixel can be examined at a time; and third, the aircraft integrates over a somewhat different angular range than the satellite in order to view the same pixel. Compared with other, indirect calibration methods, however, these disadvantages seem minor. The logistics of timing aircraft with satellite overpasses, and of viewing the same pixel, has been solved in past programs like Hovis'.

Therefore, episodic (at least yearly) aircraft calibrations of existing satellite instruments, especially the shortwave channels, should be conducted. Low-count, medium-count, and high-count pixels should all be viewed. This should be budgeted as an integral, and indeed essential, part of data analysis. A research effort along these lines has been initiated by NOAA using NASA U-2 and Lear jet aircraft. Laboratory calibrated spectrometers are being flown to calibrate the GOES VISSR and TIROS-N AVHRR visible channels.

4.2.3 Vicarious Calibration of Satellite Radiometers Using Ground Targets

It will always be necessary to test the calibration of satellite systems after launch. Such calibrations must be repeated on a quasi-regular schedule in order to detect slowly degrading radiometers. Special campaigns at large, near-homogeneous ground sites may be used for a test of different satellite instruments during the same campaign.

The basic technique is to measure relevant characteristics at the ground target at the time of the satellite overpass. These ground target characteristics are input to an algorithm which is then used to calculate spectral radiance values at satellite altitude. The algorithm may be in the form of a radiative transfer model into which ground target reflectance and atmospheric properties are input (Köpke, 1982), or in the form of a multichannel statistical regression algorithm (Deschamps and Phulpin, 1980). The process is known as the vicarious calibration technique, and it is believed to have produced calibration accuracies of approximately 6% at visible wavelengths (Köpke, 1982; and Kriebel, 1981) for Meteosat.

Experiments are now being conducted in the U.S. to determine whether or not more accurate results can be obtained by increasing the sophistication of supporting atmospheric measurements coincident with the satellite overpass. A particular emphasis is the accurate definition of aerosol angular scattering and target bidirectional reflectance near the time of satellite overpass. The technique will be applied to the ERBE shortwave scanner instrument as well as AVHRR and VISSR narrowband data. It is expected that experience gained from the present detailed experiments may lead to a simpler procedure for operational use.

4.2.4 Calibration of Ground-Based Instruments

The most frequently used ground-based instrument for surface radiation budget measurement is the broadband (about 0.3–3 μm) pyranometer that measures solar hemispheric flux. Given that such an instrument is well maintained, calibrated, and characterized for angle and temperature dependent errors, measurements should be accurate to about $\pm 1\%$. However, during operation the accuracy may be degraded substantially to about $\pm 5\%$ if the necessary care is not taken (daily cleaning, check of the leveling, check of the acquisition system, etc.). Furthermore, the person looking after the instrument has to be well trained and has to understand all the possible problems with pyranometers in order to achieve the highest possible accuracy. Unfortunately such a person is normally not available at the field station and the data have a reduced accuracy.

Silicon detectors, sensitive to radiation between 0.3 and 1.1 μm but varying with wavelength, are used with a diffuser as replacements to pyranometers. These instruments are stable and inexpensive, but they miss most of the solar infrared absorption by water vapor and clouds. Calibration procedures for these instruments are still not thoroughly worked out. Pyrheliometers, used to measure direct solar radiation, utilize the same type detectors as pyranometers, but these instruments are relatively more accurate than pyranometers because they do not contend with hemispheric glass domes that produce caustic aberration.

Solar photometry with narrowband filter instruments is used for optical depth and turbidity but other applications are possible. These instruments are used much less frequently than broadband instruments. The technology for these instruments using silicon detectors, filters, and solid state amplifiers is well developed. On the short term (a few months) at a very clear site, such as the GMCC Mauna Loa Observatory, calibrations via the Langley method can be maintained to about $\pm 0.2\%$ with thermally stabilized instruments. Long-term drifts in calibration are in the 1% range, probably caused by unstable filters.

Pyrgeometers are used to measure the broadband (about 4–50 μm) infrared radiation. Calibration of these instruments is done by viewing a surface of known emittance. Their accuracy is not well known, but measured values seem to be reasonable. In the past pyrgeometers have been used mostly by the meteorological research community interested in radiation balance studies from the surface and from aircraft. Very few are in continual use. For example, perhaps less than 50 are in use for the U.S. radiation research programs.

The major problems encountered with the uses of pyranometers, pyrheliometers, and pyrgeometers center on calibration and field maintenance. Generally, the more care given to these instruments, the better the results. Some problems encountered in the field are:

- (1) Icing of domes
- (2) Dirty domes
- (3) Off-level pyranometers
- (4) Misaligned pyrheliometers
- (5) Disinterested technicians

4.2.5 International Coordination for Ground-Based Radiation Measurements

Considering the requirements for radiation data sets in conjunction with the planned major field experiments within the WCRP, IAMAP (IAMAP No. 18, 1981) decided on a resolution calling attention to all bodies involved that the assessment, quality control, archiving, and use of radiation data measured at the surface need to be improved substantially both in quality and quantity.

IAMAP recommended that WMO should establish a regular inspection of all national measuring sites and networks to ensure adequate maintenance and documentation, accurate standardized calibration, interpolation, evaluation procedures, and rapid submission of data to the World Radiation Data Center (WRDC) in Leningrad. The primary responsibility for data reliability lies with the various national centers sending data to the WRDC.

The Meeting of Experts on the Future Activities of the WRDC (WCP 48, 1983) proposed that long-term measurements of a minimum set of four radiation budget parameters should be made and the data sent to the WRDC. The parameters are hourly averages of:

- (1) Global solar radiation
- (2) Diffuse solar radiation
- (3) Downward atmospheric radiation
- (4) Sunshine duration

Of the four quantities, downward atmospheric radiation may be considered a new quantity for most stations.

Noting the resolution of IAMAP and the recommendations of the Meeting of Experts, mentioned above, the WMO Executive Council decided that the international collection, archiving, and publication of radiation data by the WRDC be arranged according to the procedures laid out in the annex to WMO Executive Council Res. 6 (EC-XXXVI), International Collection and Publication of Radiation Data.

In this annex the importance of radiation data for the achievement of the research objectives of the World Climate Program and other international projects was recognized. Participating countries should:

- (1) Strengthen and upgrade their observing networks and practices, including regular calibration, in accordance with the guidelines to be developed by WMO;
- (2) Provide hourly sums; and
- (3) Validate the observed data according to the guidelines to be developed by WMO, IAMAP, and WRDC.

For improving the calibration procedures for pyranometers, the WMO Commission on Instruments and Methods of Observation (WMO-CIMO), through its Working Group on Radiation and Atmospheric Turbidity Measurement, suggested reducing the errors by providing calibration conditions which are similar to the conditions existing at field measurements, e.g., angle of incidence. *A three percent pyranometer accuracy should be achieved in the near future.* A report on "Recent Improvements in Pyranometry in the Light of Operational Use" is being drafted and will be submitted for publication in the WMO series on Instruments and Methods of Observation. A thorough investigation and characterization of a group of pyranometer types manufactured by Eppley, Kipp and Zonen, Schenk, Swissteco, and EKO has been performed by a task group constituted by the International Energy Agency (IEA). The results of these activities will soon be available as an IEA report.

The addition of new radiation measurement stations should not be at the expense of the quality of already existing global radiation stations. On the contrary, the network density may be reduced if this will ensure that the remaining stations are maintained and operated at the desired high levels.

Downward atmospheric radiation is measured by pyrgeometers or derived from measurements of total downward radiation by pyrrometers. Some types of pyrgeometers are known to exhibit rather large measuring errors particularly by solar heating of the cover dome. The Royal Meteorological Institute of Belgium has started laboratory investigations on different types of pyrgeometers and pyrrometers.

Diffuse solar radiation is most often measured by pyranometers equipped with a shade ring screening the direct solar radiation. To achieve high measuring accuracy, the readings have to be corrected for the portion of the diffuse solar radiation which is screened by the shade ring. Shade ring correction methods have been proposed and are critically summarized in WMO No. 15 (1984).

Activities which would improve ground-based radiation measurements are:

- (1) Calibration of surface radiation instruments should be performed by the National Radiation Centers (NRCs) of the participating countries. If the participating country does not operate an NRC, arrangements with a country which operates an NRC should be sought for assistance.
- (2) Calibration procedures should follow the WMO Guide to Instruments and Methods of Observations (WMO No. 8, 1983).
- (3) Network extension or densification should not be at the expense of data quality of the existing stations. High quality of data may be obtained not only by careful calibration but by
 - a. proper installation
 - b. frequent inspection and maintenance
 - c. adequate training and instruction of personnel involved
- (4) When measuring diffuse solar radiation with the help of shade ring pyranometers, proper shade ring corrections have to be applied. For details, see WMO No. 15, 1984.
- (5) The precision of pyrgeometers and pyrrometers used for measuring downward atmospheric radiation has to be improved. Both systematic characterizations and comparisons of instruments with a silicon dome, a polyethylene cover, and with open sensors are needed.

4.3 VALIDATION

Validation covers a wide area of activities which are needed in order to convert a measured signal into a geophysical quantity with known accuracy. In this report validation is restricted to the attempt to assess the accuracy of surface radiation budget components estimated from satellite data by comparing them to other data. Either narrowband or broadband radiation measured at the ground or from an aircraft is considered for this purpose.

4.3.1 Validation by Existing Surface Measurements

The number of surface stations with well-calibrated instruments for solar radiation flux measurements is adequate for monthly means and thus for climate applications over parts of some continents. It is inadequate for most tropical areas. In view of the possibility of deriving surface radiation budget components from satellite data, there is no need for a denser continuously measuring network in midlatitude continental areas. However, for limited time periods, very dense networks are needed for the assessment of correct temporal and spatial sampling for deriving an average value over the size of a satellite pixel or over a model grid element.

An improvement, at least temporarily, in the tropics and in high latitudes is necessary in order to validate satellite-derived solar fluxes under all surface and atmospheric conditions.

Downward longwave fluxes are measured by only a small fraction of surface stations measuring solar radiation fluxes. The relative accuracy reached is inferior to the shortwave measurements, especially for daytime measurements at high insolation. Over surfaces with high emissivity the upward longwave flux is presently more easily determined from surface temperature and surface emissivity than from direct measurements.

Since the highest values of surface longwave net flux occur over hot deserts near sunset, the enlargement of the longwave radiation flux network is most urgently needed there. Also, more stations are needed for areas with highly variable downward longwave fluxes under clear skies due to strong humidity and temperature fluctuation (for instance, subtropical areas with a dry and a rainy season). The enlargement of the longwave flux network is desirable because of the presently inadequate capability of deriving surface fluxes from satellite data even for cloudless areas.

4.3.2 Validation by Dedicated Field Experiments

The inaccuracy of radiation flux measurements with pyranometers, pyrrometers, and pyrgeometers (often higher than 10 Wm^{-2} even for monthly averages); the accuracy needed for climate applications; and the lack of information on aerosol particles, water vapor, and cloud microphysics clearly point to the need for dedicated field experiments for the validation of SRB components estimated from satellite radiances.

4.3.2.1 Longwave experiments over land

A recent international intercomparison of 37 longwave radiation models for the clear atmosphere (Intercomparison of Radiation Codes for Climate Models [ICRCCM]) revealed large disagreements, on the order of 35 Wm^{-2} at the surface for all gases and 70 Wm^{-2} for a pure H_2O atmosphere. Line-by-line models agreed within a few Wm^{-2} , but ICRCCM concluded they could not be used as an absolute standard because of uncertainties in line shape and continuum absorption.

In order to resolve these huge discrepancies, ICRCCM recommended a field program. Preliminary formulation of such a program, called CLAIRE (Clear Air Infrared Radiation Experiment), was completed in June 1985. CLAIRE's goal is to measure the spectral radiance, primarily at the surface, with 5 cm^{-1} resolution or better, and to use these data to determine which models, if any, are correct.

Three key aspects of CLAIRE are as follows:

- (1) Excellent characterization of the radiatively important atmospheric variables;
- (2) Redundancy: at least three spectrometers measuring simultaneously; and
- (3) Real-time comparisons of measurements with models.

CLAIRE can contribute to a basic understanding of the downward longwave component of the SRB, which is the component most difficult to infer from space. Additional spinoffs relevant to SRB include:

- (1) The relation of narrow (satellite-type) channel radiances to the spectrally integrated flux;
- (2) The proper conversion from radiance to flux; and
- (3) Possible new methods for routinely measuring SRB (e.g., there may be a strong correlation between window-region radiance and spectrally integrated flux).

While CLAIRE at first is designed to resolve the specific discrepancies uncovered by ICRCCM, it also offers the opportunity to substantially improve our understanding of SRB.

Because serious questions have been raised by ICRCCM about the accuracy of longwave radiation models, at levels far exceeding the 10 Wm^{-2} required by TOGA and WOCE, an experiment like the proposed CLAIRE should be supported as a necessary prerequisite to a proper theoretical understanding of SRB.

4.3.2.2 *Shortwave experiments*

A recent study sponsored by the IAMAP's Radiation Commission (Lenoble, 1985) has shown that for horizontally homogeneous, plane-parallel atmospheres, shortwave radiative transfer codes are in substantial agreement for a given set of input data. For these assumptions the problem that remains is that of providing the vertical distributions of the important constituents (principally clouds, aerosols, and water vapor) together with their optical properties and spectral as well as angular variations of the surface reflectance. In addition, these models combined with methods for establishing realistic input data are largely untested against observations. Furthermore, the plane-parallel approximation does not give accurate results for the frequently encountered condition of broken cloud fields so that appropriate models or parameterizations must be developed and verified for that case. Dedicated SW field experiments devoted to these problems would contribute substantially to improving the accuracy of methods to derive SRB components from satellite observations.

Airborne and ground-based measurements of the SW anisotropy especially for broken cloud conditions should be performed in order to show their impact on SRB estimates from satellite data. Studies now being planned as part of FIRE will address this problem and other experiments should be encouraged. For example, the airborne version of the Conical Scan Radiometer (AVCSR), presently under development in Europe, is specially designed to investigate the influences of the anisotropy of the radiance field. It could be an efficient tool in the needed experiments. For validation of SW surface fluxes derived from satellite observations, the variable aerosol scattering and absorption needs to be incorporated both into the algorithm (either implicitly or explicitly) and the validation data set. Presently there is neither a reliable climatology of aerosol types and concentrations nor an assignment of concomitant optical properties. The workshop recognizes that an International Aerosol Program whose objectives may fit the needs for surface flux measurements is now under development. Dedicated SW field experiments combining radiation models and detailed observations should be a part of that program.

It is noted that the intercomparison of SW radiation codes being performed during the second step of the ICRCCM program should allow a more detailed evaluation of the reliability of radiative transfer calculations and their influence on the accuracy of derived SW surface fluxes.

4.3.2.3 *Validation measurements: Ships of Opportunity Program*

The satellite-based radiation estimation schemes must be shown to meet the accuracy requirements of the TOGA and WOCE experiments. For this purpose, validation is required over the entire range of atmospheric and oceanic conditions, including both geographical and seasonal variations. Thus, in addition to specific regional validation campaigns, a continuous program to obtain radiation measurements from ships of opportunity is required. The validation technique used will be to compare the mean measured and estimated fluxes over periods of a week to one month or more. The program should continue for the duration of TOGA and WOCE.

The measurement accuracy required is 10% for the longwave and 5% or better for the shortwave fluxes. Such accuracies are achievable, but only if the measurement is made with great care. Thus the requirement is for a relatively small number of ships, perhaps 10 to 30, equipped with calibrated and well-maintained sensors. Poor quality measurements, even if obtained from a large number of ships, will not have any value.

Implementation of the program requires that one or more research groups be made responsible for satellite radiation scheme validation using ships of opportunity data. Such a group must prepare instrument packages to measure the downward fluxes of shortwave and longwave radiation and be responsible for mounting these packages on chosen ships and for processing the data after use.

Validation must be undertaken in collaboration with groups operating satellite-based retrieval schemes and the results published jointly. Continual calibration of the instruments used will be vital and all instruments must be intercompared. Thus, if more than one group is involved, transfer-standard instruments must be exchanged between groups.

For utilization of the validation results ancillary data must be available from the chosen ships. Rather accurate measurements of near-surface air temperature ($\pm 0.5^\circ\text{C}$), specific humidity ($\pm 1\text{ g/kg}$), bulk ocean surface temperature ($\pm 0.3^\circ\text{C}$), and position are required. It is also highly desirable that WMO-type cloud observations and radiosonde temperature and humidity profiles be available. Quality control of the data may require monitoring of ship heading and relative wind direction to assess the obscuring effects of masts and funnel smoke. Selection of the ships will therefore depend on:

- (1) Willingness of ship personnel to accommodate and maintain the instrumentation
- (2) Existing availability of the ancillary data required
- (3) Area of ocean in which ship will operate

It is likely that research ships involved in the TOGA or WOCE programs will be most appropriate. These carry interested scientists, have good navigation, and will operate in predetermined survey areas. Many have autologged meteorological instruments and a few conduct radiosonde ascents. However, consideration should also be given to other ships, particularly those involved in the World Weather Watch (WWW) Automated Shipborne Aerological Program (ASAP) or the Integrated Global Ocean Services System (IGOSS) expendable bathythermograph (XBT) program.

The instrument package must be designed to be self-recording in use, with maintenance limited to regular sensor cleaning. Provision of an optional monitor display is desirable. It is strongly recommended that a sensor be included to detect periods of ship radio transmission and that the recorded data be flagged accordingly. For calibration the instruments must be removed or exchanged at regular intervals, perhaps 6 to 12 months.

The program will require special funding support for purchase of instrumentation, to employ technicians to build, calibrate, and maintain the packages, and to cover shipboard installation costs. It will also be necessary to canvas the support of research scientists and other agencies with access to suitable ships. The importance of the program to surface radiation budget estimation within the WCRP must be stressed.

4.3.2.4 *Aircraft experiments*

The vast majority of techniques for estimating the SRB from satellite radiance data have employed fixed point surface observations for the purpose of validation. However, perhaps the most accurate shortwave and longwave irradiance data have been collected by airborne sensors during the various GARP experiments (e.g., GATE, JASIN, and MONEX). Most important, these data have often been collected at times simultaneous with the observation of many of the variables necessary to validate radiation models as well as SRB infrared schemes.

Several investigators have used some of these data to calibrate radiation models (e.g., Ackerman and Cox, 1982; and Ellingson and Serafino, 1984). In general, these investigations have shown that for clear sky conditions, the vertical distributions of the upward and downward fluxes may be calculated to within the accuracy of the observations (i.e., $\pm 2\%$ shortwave and $\pm 5\%$ longwave relative accuracy). Somewhat larger ($\pm 5\text{--}10\%$) differences have been found for some homogeneous cloudiness conditions (Slingo and Schrecker, 1982; and J. Schmetz et al., 1981).

Although many aircraft data sets are available at times simultaneous with satellite measurements, there have only been a few attempts to use data gathered at low altitudes for validating SRB

estimation techniques. This is probably due to a lack of coordination of the aircraft path with satellite overflights. Nevertheless, the data analysis and display techniques which are available offer the possibility for searching data series for usable satellite-aircraft data sets.

Several new large field programs which will employ research aircraft are planned for the near future (e.g., STORM and FIRE). Because these experiments will study the development of different cloud systems, it seems important to recommend that these experiments measure the various components of the SRB at the ground and from aircraft, at times planned to make maximum benefit of satellite observations.

4.3.3 Validation Strategies

4.3.3.1 *Comparison of satellite and surface measurements*

The problem with comparisons of satellite and surface measurements is one of resolution and the high degree of inhomogeneity on the scale at which surface measurements are made. For example, the work of Pinker (1985b) shows a fairly homogeneous surface under clear sky conditions based on 1-km AVHRR satellite imagery over a 50×50 km area. On the other hand, Landsat and aerial photography for the same area reveals a very patchy surface, following the variations of vegetation cover and land use.

Spatial inhomogeneity is a much more serious problem for upward than downward flux because of surface reflection, large surface temperature effects, and the nature of the angular integration problem. It is not a problem over large bodies of deep water and over flat terrain with uniform surface type. Terrain is an important factor due to shading which, of course, varies with the diurnal cycle. Variability of LW upward flux generally occurs under clear sky conditions where there are changes in soil type and vegetation cover (e.g., forest versus bare soil or rocks) and where terrain height variations with nonvertical Sun produce shadows. Observations under those conditions reveal variations in surface temperature of as much as 30°C and variations in net flux (SW + LW) of several hundred Wm^{-2} .

In addition to surface inhomogeneities, which affect upward SW and LW flux at the surface, there can also be atmospheric inhomogeneities (e.g., due to clouds) which affect the flux estimates based upon satellite radiance measurements. There is also an "adjacency" effect, that is, the effect of neighboring areas on the scattered light at any particular point. As a rule of thumb, the adjacency effect is important when the spatial inhomogeneity is on a scale comparable to or smaller than the height of the atmospheric scattering layers. When one performs averages over areas larger than about 10 km, the adjacency effects largely cancel out. The problem then becomes one of sampling.

In order to compare satellite-based estimates of surface flux with surface measurements, the following strategy should be adopted. It is based upon two approaches for handling surface inhomogeneities:

- (1) *Dense local network*, covering a small area of about 10 km on a side. Within that area, classify the surface and deploy surface radiometers within each surface class. Then for any satellite footprint within the area, one can integrate the surface radiometer measurements from each surface type, with appropriate weights, to determine the average fluxes within the satellite footprint. This can be done for instantaneous measurements as well as monthly means.
- (2) *Extended area network*, covering about 500 km on a side and carefully selected to be flat and as homogeneous as possible. Within that area radiometers would be deployed more or less uniformly over the area, but with care to avoid any rare or nonrepresentative terrain. Comparisons would be statistical, using monthly means.

Both approaches should be used because they each have advantages and drawbacks. Our strongest recommendation is for a nested grid in which the dense local network would be imbedded within an intermediate network of about 70 km on a side which, in turn, would be imbedded within the extended area network. The reason for the nested grid is that satellite-based estimates may work differently on different scales and validation should be done on the smallest scale that could encompass several pixels (10 km) as well as on the scale at which data sets would be developed for climate use (500 km).

The number of radiometers to be deployed in each network would depend on sampling studies that take into account the number of surface classes (for the dense local area network) and the structure function for the radiative fluxes (for the extended area network).

4.3.3.2 *Sampling strategy*

Measurements and estimations of the surface radiation budget are discrete in time and space. Therefore, the estimation of area and time averages must be based on studies which determine the required frequency or density of measurements in time and space, respectively.

There are two main approaches to the solution of this problem. The first, a theoretical approach, requires a careful spectral analysis of the target areas to determine the spatial scales of variability for the appropriate surface properties (e.g., albedo, bidirectional reflectance, emittance, etc.). The temporal variability of surface properties is primarily seasonal due to changes in vegetation and soil moisture. Thus, the temporal variability of the atmosphere needs to be determined via time spectral analysis not only for different seasons but for many geographical areas. Adequate cloud fluctuation statistics (Cahalan et al., 1982) are most important. It is then possible, based on spectra of atmospheric and surface variability, to determine the proper sampling strategy for the required accuracy in time and space.

The second approach is more empirical: a high-resolution measurement in time and space is stepwise degraded. The degradation of the product derived from the poorly sampled data is then compared with the original high-resolution result or with ground measurements. This method has the advantage of being easily tractable; however, it may be impossible to determine whether the high-resolution sampling was appropriate.

Studies are needed to define the time and space spectra of natural targets (i.e., surface, cloud structure, aerosol, and water vapor structures) and to relate them to satellite and surface measurements of the surface radiation budget in order to estimate the required sampling rate and integration times of a sample. Special surface stations and aircraft campaigns with high-resolution measurements are needed for this purpose.

4.4 SUMMARY OF RECOMMENDATIONS

4.4.1 Calibration

- (1) Measurements from satellite instruments must be calibrated independently (either directly by onboard techniques or indirectly by measurements from ground stations, aircraft, or by transferred calibration from other satellites) before they are validated by different ground or aircraft data.
- (2) Episodic high-altitude aircraft flights are a practical method to calibrate existing satellite radiometers. These flights should be part of the routine data analysis.
- (3) Future satellite radiometer systems should include absolute calibration traceability and characterization of the spectral and angular response of the instruments.

4.4.2 Validation

- (1) Only carefully selected ground truth stations, preferably including the NRCs, should be used for validation of satellite-derived SRB products. If possible, the ground truth station should be instrumented to provide the necessary auxiliary data, for instance, aerosol optical depth, water vapor column content, and vertical profiles.
- (2) The number of ground stations measuring the downward longwave flux should be increased.
- (3) Ships with meteorological observations and preferably with aerological soundings should be equipped with an SRB measurement package for the validation of satellite SRB products over ocean areas.
- (4) Because serious questions have been raised by the ICRCM study about the ability to calculate the longwave SRB to 10 Wm^{-2} , experiments, such as the proposed CLAIRE project, should be supported as a corequisite to understanding the SRB.
- (5) Validation studies involving comparisons of satellite and surface measurements should be conducted with a nested grid of surface measurement stations including high-density networks. Detailed sampling analyses should be part of these studies.

SECTION 5

DATA SETS DEVELOPMENT

5.1 INTRODUCTION

Data sets development to support research and calculations of surface radiation budget quantities is necessary to provide data with characteristics appropriate to climate research. Elements of the problems with existing data sets include: (1) lack of certain types of observations, especially at the surface; (2) lack of accurate calibration or validation for some measurements; (3) dispersed data holdings in multiple formats; and (4) uneven completion of documentation.

For the production of the surface radiation budget (SRB), we will require a data system capable of accessing all necessary data, calibrating them, then processing them to obtain the SRB, and validating the results. The methods for deriving the different components (shortwave and longwave) of the SRB are in different stages of development. Furthermore, the needs differ for different applications. It is essential that this data system be able to accomplish different functions, which are: (1) interaction and support of existing (or planned) climate research programs; (2) validation, inter-comparison, and error analysis of existing algorithms; (3) calibration of instruments; and (4) instrument, algorithm, and model development. These functions are described in section 5.2. The details of the data sets necessary for accomplishing these functions are provided in section 5.3, characteristics of the data system are in section 5.4, and recommendations are given in section 5.5.

5.2 FUNCTIONS OF DATA SYSTEM

The ultimate objective of the data system is to transform a set of raw measurements into a set of geophysical quantities, in this case the components of the surface radiation budget: upwelling, downwelling, and net shortwave radiation; upwelling, downwelling, and net longwave radiation; total (shortwave plus longwave) net radiation; and the shortwave albedo, longwave emittance, and temperature of the surface. Accomplishing these goals on a global basis means that the surface budget will rely heavily on satellite data, thus requiring inference of the surface parameters through empirical and/or physical models. Consequently, the data system has to be flexible enough to accommodate new algorithms based upon new instruments and improved theoretical and empirical models. *It is imperative that the system not be fixed and rigid.*

A flexible data system should satisfy a variety of uses. It should provide data necessary to develop methodologies, techniques, and algorithms, as well as the final set of geophysical quantities such as might be used in GCMs. The former implies data or subsets of data that contain sufficient detail for development of new algorithms and the latter implies outputs that are easily accessed by the user community.

5.2.1 Interaction and Support of Programs

Some existing or planned climate research programs have needs for the SRB in order to accomplish their scientific objectives. This is the case for TOGA and WOCE, which have established quantitative requirements for SRB. In both the ERBE and ISCCP projects, the surface radiation budget can play a useful role by providing additional sensitivity checks for the radiation models employed for analysis. The key cloud radiative model issues that are important to ERBE and ISCCP analyses and to the calculation of the surface radiation budget are the effects of cloud size distribution and morphology on the angular and spectral dependence of radiances. Both intensive surface radiation data analysis for algorithm development and validation and surface radiation budget climatologies can contribute to accomplishing the ERBE and ISCCP science objectives. Coordination

of any such intensive surface radiation budget studies with ERBE and ISCCP validation studies and with field programs associated with ISCCP and ISLSCP (i.e., FIRE and FIFE) can be especially productive for improvements in radiation models.

The data produced by the system should be readily available for a number of other uses: climate monitoring, diagnostic studies, model forcing, and validation. This requires data easily accessible on a variety of spatial and temporal resolutions (e.g., grid point to large scale average and daily to monthly to seasonal) and on several map grids.

Further, the data system should support data continuity, that is, as more accurate estimates of the surface radiation budget become available, earlier estimates of surface radiation budget should be recalculated. This is an *absolute necessity* for long-term monitoring and diagnostic studies.

5.2.2 Validation, Intercomparison, and Error Analysis

One of the major reasons for developing data sets is for the validation and intercomparison of algorithms for producing surface radiation budget. These data sets are typically of higher spatial and temporal resolution than those of the SRB climatological products. There are several alternatives for producing the SRB end products, and high-resolution validation data sets can contribute significantly to distinguishing between these alternative methods. The second major reason for providing this type of data set is to quantify the statistics of representative areas, so that systems for producing global data sets of surface radiation budget will be able to identify the major sources of error and minimize them.

There are several areas of concern for algorithms that convert satellite data into surface radiation budget; the main problem is to establish how critical they are for building up a climatology. Foremost among these are the difficulties caused by cloud property variations in space and time and the lack of reliable, retrievable properties below the radiating cloud tops. Optically thin clouds may appear to be indistinguishable from broken, thick clouds and multi-layered systems may also cause difficulties. Accordingly, direct measurements of area averages of the surface budget are needed for areas in which the satellite data are used to deduce the surface budget. The derived surface radiation fluxes should rely on models of poorly understood phenomena as little as possible.

Another requirement for data sets to conduct extensive studies is the quantification of the spatial structure and temporal correlations that can be used to quantify the design of future measurement systems for the surface radiation budget. Specifically, the panel recommends the quantification of spatial structure in terms of two-dimensional Fourier-spectra or autocorrelation functions, the characterization of broken cloud fields in terms of the aspect ratio and intercloud spacing, and similar quantifications for other types of spatial inhomogeneity. Likewise, in temporal variability, the panel strongly urges the quantification of surface radiation variability in terms of autocorrelation functions or their spectral transforms. The presence of periodicities in the data must be known in order to quantify the gains to be made in reducing variability by longer data records, as well as to estimate the number of degrees of freedom that are appropriate to a given data set.

In situ data to be obtained for use in validation of algorithms used in conjunction with satellite data are of two kinds: (1) the direct measurement of shortwave and longwave irradiances, and (2) the substitute or support quantities which must be inferred from the satellite data implicitly or merged with the satellite data explicitly from other data sources. Examples of the latter quantities are transmittance of the clear sky, water vapor and temperature profiles, and cloud properties (e.g., amount, type, and base heights for up to three levels).

5.2.3 Calibration of Instruments

Calculation of the separate elements of the surface radiation budget with an accuracy sufficient for climate studies ($\pm 10 \text{ Wm}^{-2}$) requires accurate calibration and intercalibration of all instruments used. Calibration will require careful collection of several special data sets which allow intercom-

parisons of instruments over a wide dynamic range with known sources or targets or other calibrated instruments. In addition, data sets should be defined to develop and support methods for routine calibration monitoring over the period of a climatology data collection effort.

Much of the data that are expected to be used in the estimation of the surface radiation budget come from satellite radiance measurements in narrow spectral bands with incomplete calibration systems. Accordingly, a significant effort is required to produce surface radiation budget estimates for broadband fluxes in absolute physical units.

The Earth Radiation Budget Experiment scanner data provide the current state of the art in in-flight calibration of longwave and shortwave radiances, and come closest to direct measurement of broadband, upwelling radiation components at the top of the atmosphere. Accordingly, these data are primary candidates for calibration of broadband radiance estimates of other satellite systems that may be used in surface radiation budget estimates. They should also be used directly in the estimation of the surface budget itself.

5.3 DATA SETS REQUIREMENTS

5.3.1 Global Studies

An opportunity for thorough diagnosis of the radiative forcing of the atmosphere and ocean, especially the central role of cloud variations in determining this forcing and its sensitivity to climate change, is provided by the combination of ERBE, ISCCP, and SRB studies. This opportunity is greatly facilitated by coordination of calibration and validation activities and production of climatologies in compatible formats.

The existing or currently planned data sets for ISCCP, ERBE, and ISLSCP are expected to provide the majority of the global satellite data sets required for surface radiation budget studies. These will include global sets (at already prescribed scales) from AVHRR, GOES, and TOVS systems. The implementation of a "super vegetation index" AVHRR data set being considered by NOAA should be encouraged. This set will include on a daily basis (at a latitude-longitude resolution of about 20 km) the radiances (counts) for AVHRR channels 1 and 2 and brightness temperatures for channels 4 and 5; coverage will include the latitude range 55°S to 75°N. Also included will be information on solar zenith angle, satellite scan angle, and normal latitude-longitude navigation.

The ISCCP data archive is located at NOAA/NESDIS and, thus, it is associated with the complete satellite data holdings of NOAA. The specific ISCCP data holdings will include:

- (1) Reduced resolution radiance images from all available operational weather satellites at a nominal 10 km, 3 hour resolution for geosynchronous satellites (GOES, GMS, and Meteosat) and GAC data from at least one polar orbiter. Data from all radiometer channels are present. Data collection began in July 1983.
- (2) Reduced resolution radiance images (approximately 30 km for all satellites) in uniform format with normalization/calibration and navigation information appended.
- (3) Correlative data sets, including TOVS products (temperature and humidity profiles, ozone abundance, and surface temperature), NMC surface station reports (surface temperature, dew point temperature, and cloud cover), and operational snow (NOAA) and sea ice (U.S. Navy reports), remapped into common map grids with only a modest amount of space and time interpolation (real data flagged).
- (4) Cloud climatology products providing the equivalent of a complete atmospheric column description at 250 km (nominal) resolution every 3 hours that include atmospheric temperature and humidity profiles, ozone column abundance, effective surface

temperature and reflectance, cloud cover fraction (and uncertainty estimate), effective optical thickness, effective cloud top temperature and pressure, and satellite-measured radiances. Additional cloud statistics and cloud classification information will be provided, as well as general data sets used in the analysis, such as topography and vegetation classifications. Several of these properties are *effective* radiative values; conversion to proper physical quantities may require further study or modeling.

5.3.2 Program Support

5.3.2.1 *Ocean processes: TOGA and WOCE*

The only requirement for radiation data stated in the TOGA Scientific Plan is that for incoming shortwave radiation flux. The requirement is for an accuracy of 10 Wm^{-2} for monthly averages in each 2° latitude by 10° longitude box in the tropical zone (strictly $+20^\circ$ latitude, but taken to be $+30^\circ$ latitude in many studies). Concerning the net heat flux variations associated with the Pacific El Niño/Southern Oscillation (ENSO) phenomenon, which are of order 200 Wm^{-2} , an accuracy of 20 Wm^{-2} rms for the mean flux (averaged as defined above) would be appropriate, although an accuracy of 40 Wm^{-2} would still be useful. However, interannual variability in the tropical Atlantic and Indian Oceans is substantially less than in the Pacific. It would seem appropriate therefore to define, on a global basis, a benchmark accuracy of 10 Wm^{-2} for the space- and time-averaged surface net radiation budget (shortwave and longwave combined). Estimates to lower accuracy will still be valuable for TOGA research; however, the research goals may become more limited if lower accuracy is achieved.

Although the above accuracy requirements are defined in terms of monthly mean values, for some TOGA research projects data on higher time and space resolution are required. In general the surface radiation budget is not likely to be required at a resolution greater than one day and 2° lat. \times 2° long.

Data availability is also an important consideration both in terms of timeliness and ease of access. Surface radiation budget estimates for TOGA should be available within 6 to 18 months of observation. Present planning envisages an Air-Sea Interface Data Centre producing fields of the mean surface fluxes as a non-real-time, operational, level 3 data product. The SRB data should be made available to this program in level 2 (or level 3 on a standardized grid) form. The SRB database would form one node of a data-conduit-based data processing network. In the scheme proposed, individual researcher groups, or operational groups responsible for a particular product, each represent network nodes. The network nodes may interact directly or, more conveniently, through a "data conduit." The data conduit is a group (or node) whose purpose is to obtain and "package" the data in a convenient form for distribution to other nodes. There is also need for a data coordination group to collate and make available information concerning data availability. This group may be collocated with the data conduit, although this is not necessarily so.

The TOGA program commenced on 1 January 1985 and will continue for 10 years. It is therefore important that consideration be given to obtaining the SRB retrospectively from the start of 1985.

WOCE planning centers on the availability, from about 1990, of satellites which will give greatly improved observations over the global oceans of variables such as wind stress and surface elevation, and also on the present rapid development of computer technology. The latter is important since it will allow high-resolution numerical modeling of the global oceans. One goal of WOCE is to collect the data necessary to develop and test ocean models useful for predicting climate change. It will also be necessary to determine the representativeness of the specific WOCE data sets for the long-term behavior of the ocean, and to find methods for determining long-term changes in the ocean circulation.

The surface heat flux contributes to the forcing of the ocean thermohaline circulation and thus must be estimated as part of WOCE. Accuracy and data availability requirements for the SRB for WOCE purposes are similar to those for TOGA, and it is expected that WOCE data management will build on that developed for TOGA. Note, however, that WOCE requires monthly mean SRB data globally with 5° lat. × 5° long. resolution (2° lat. × 5° long. in the tropics). WOCE is planned to commence in 1990 and continue through 1994.

5.3.2.2 Radiation and cloud studies: ERBE and ISCCP

Data sets needed to improve the ERBE and ISCCP radiative model treatments of cloud effects on the angular and spectral dependencies of radiances are:

- (1) Very high-resolution, limited area, satellite imaging data covering sufficiently long time periods to provide statistics of cloud size distribution and tests of varying resolution for retrieved cloud and surface properties. Such data are available in scattered archives, but special efforts are required to collect the appropriate data subsets for case studies and to improve the accuracy of navigation and calibration information. Some data sets of this type will be produced by FIRE and FIFE.
- (2) Simultaneous, coincident, multidirectional observations of various cloud and surface types on scales ranging from individual cloud elements up to mesoscale cloud fields. These observations, from combinations of ground-based, aircraft, and spacecraft radiometers, can be used to study the effects of cloud morphology and microstructure on the angular variation of radiances on mesoscale to synoptic scales. This study can improve interpretation of cloud properties retrieved from satellite data (ISCCP) and extend these to modeling of radiative fluxes at the top of the atmosphere and the surface. Data of this kind can be extracted from the ISCCP and Wisconsin University archives, but this requires a large processing effort. Several such data sets will be produced by FIRE for continental cirrus and marine stratocumulus situations. Limited data sets already exist for MILDEX.
- (3) ERBE and Nimbus-7 planetary radiation budget data and combinations of narrowband, multispectral radiances. Comparisons of narrowband and broadband radiances at many wavelengths from narrow and wide field of view instruments provide ways to check the angular and spectral relationships between these measurements and radiation models. These data are all available in the Goddard Space Flight Center archive, but selection of specific case studies is necessary.
- (4) Coordinated ground-based, aircraft, and satellite multispectral radiance measurements, especially over snow- and ice-covered surfaces, to confirm calculations of downwelling and upwelling radiation in partially or completely cloudy situations. The satellite cloud properties need to be augmented with cloud base temperature and surface radiative property observations. Some data of this kind are available but are scattered among individual scientists. FIRE and FIFE will collect such coordinated data sets for cloudy and clear conditions, but special effort will be required to obtain such data over snow- and ice-covered surfaces which are crucial to climate sensitivity.

5.3.3 Special Studies

5.3.3.1 Pilot studies

For pilot studies to verify models for calculating shortwave and longwave irradiances at the sea surface, several data sets are already available (see Table 5.1 for some examples). These include direct measurements of shortwave and longwave irradiances obtained during field experiments. In conjunction with the surface irradiances, we need high-quality surface observations of dry and wet bulb temperature, sea surface temperature, and cloud observations. Radiosonde measurements several times

Table 5.1 Direct Measurements of Surface Radiation Budget Components over the Ocean**

Experiment/ Site	Time Period	Components:(*)					Data Available	Duration
		E _S	M _S	E _L	M _L	Net		
JASIN N. Atlantic 60 N, 12 W	Summer 1978	Y	Y	Y	Y	Y	10-minute or hourly means of all radiation components	7 weeks
STREX N. Pacific 50 N, 140 W	Autumn 1980	Y	I	Y	I	I	10-minute or hourly means of shortwave and longwave irradiance	6 weeks
Pre-MIZEX Bering Sea	Winter 1981	Y	N	Y	I	I	Hourly means of shortwave and longwave irradiance	4 weeks
MIZEX-East Greenland Sea	Summer 1983	Y	N	Y	I	I	30-minute means of shortwave and longwave irradiance	7 weeks
MILDEX E. Pacific 30 N, 130 W	Autumn 1983	Y	Y	Y	Y	Y	5- or 30-minute means for components at 2 platforms	3 weeks
MIZEX-East Greenland Sea	Summer 1984	Y	Y	Y	I	Y	30-minute means for components at 2 platforms	4 weeks
FASINEX Bermuda 30 N, 70 W	Winter 1986	Y	I	Y	I	Y	Planned instrumentation on 2 Ships (with shortwave in 2 wavelength bands)	4 weeks

(*) E_S = shortwave irradiance, M_S = shortwave radiant exitance

E_L = longwave irradiance, M_L = longwave radiant exitance

Legend: Y = yes; N = no; I = calculated by indirect method or model

(**) Developed by K. B. Katsaros and R. J. Lind

daily are also desirable. These support data are necessary in order to explain any differences between modeled and measured irradiances.

Completed data sets of surface measurements for proposed surface radiation budget pilot studies should be merged with multiple-sensor satellite data (AVHRR, GOES, TOVS) especially for the time and place of the pilot studies [e.g., as planned for FIRE (ISCCP), FIFE (ISLSCP), etc.].

5.3.3.2 Surface reflectance

A large quantity of useful data on surface spectral reflectances and bidirectional reflectances for various spectral intervals is available, but it is scattered among a number of sources not readily available. For use in algorithm development, sensitivity studies, and other applications, it is recommended that a reference set of surface spectral reflectances and spectral bidirectional reflectances be collected for a variety of surface types and put into a readily accessible publication and digital form.

5.3.3.3 Longwave flux over oceans

Since direct measurements of longwave irradiances at the ocean surface are almost nonexistent, it would be valuable to obtain such measurements in conjunction with many oceanographic cruises. Particularly useful ones would be cruises for air-sea interaction studies, since typically the relevant support data would then be obtained. Air-sea interaction experiments planned in the near future include: the Frontal Air-Sea Interaction Experiment (FASINEX), February 1986, near Bermuda; the Humidity Exchange over the Sea Experiment–Main Experiment (HEX-MAX), October–December 1986, North Sea; and the Winter-MIZEX, winter 1988, Greenland Sea.

5.4 DATA SYSTEMS CHARACTERISTICS

5.4.1 Summary of Data Set Characteristics

Data sets needed to support SRB research can be characterized as widely dispersed with uneven levels of documentation and varying formats. Most of the larger data sets are held in numerous format archives, but important observations from specific projects or individual investigations are held by individual scientists or institutions that do not provide archive services. Documentation does not always provide complete information about data coverage and resolution, calibration, quality control, analysis techniques, and format. Formal archives usually provide more documentation, but not all such information is available. Many data sets, especially those providing regional-to-global coverage over long time periods, are very large volume. Sources of data are from ground-based, aircraft, and spacecraft platforms.

5.4.2 Data Management Issues

The primary data management problem that must be resolved to support SRB research is to improve access to the large, widely dispersed data sets currently available or being produced. Two research scenarios are described below to illustrate data system functions, but the key data management issues are common to both. These issues are: (1) lack of a useful catalog; (2) uneven documentation of observation/analysis systems; (3) lack of complete calibration information; and (4) multiplicity of data formats. Production of a data catalog is necessary to exploit *existing* data resources for method and model development and for coordinating future study results toward eventual creation of a SRB climatology. Completion of instrument characteristics, calibration, and analysis method descriptions are necessary to employ multiple data sets in a consistent analysis. Multiple formats create a practical problem for investigators who must bring together these data with differing resolutions and coverage statistics to complete the analysis. Significant effort for reprocessing or reformatting data is often necessary.

The two types of research, illustrated by the scenarios, are referred to as pilot studies and surveys.

- (1) Pilot studies are *intensive* multidata studies usually of limited coverage but high resolution to develop instruments, analysis algorithms, and radiative models, and to test calibration and validation procedures. The pilot studies use fewer data, but require much more processing to find and select samples from many sources and to solve problems of varying spatial/temporal characteristics, varying calibration quality, and varying navigation quality.
- (2) Surveys are *extensive* multidata studies to obtain larger area (global) coverage over longer time periods to support climatological research. Surveys seek statistics and can usually tolerate less quality control, but must process much larger data volumes to obtain proper spatial/temporal coverage.

5.4.3 Data Management Systems

Data management problems for pilot studies and surveys suggest two types of data systems to accomplish the research objectives.

- (1) Dispersed processing and holdings with central information and coordination: (a) creation of a central catalog of relevant data holdings (location, contents, and characteristics) for the SRB pilot study; (b) coordination of pilot studies which acquire and analyze data sets independently; (c) return of these special data sets and their analysis products to some archive; and (d) addition to the central catalog of these new data sets with a record of their use.

- (2) Dispersed data collection with central processing and holding: (a) coordination of multiple data centers to collect, reduce, and format data in a routine, uniform fashion; (b) central analysis of all data sets using "standard" algorithms; (c) central archival of data and products with catalog of contents and characteristics.

5.5 RECOMMENDATIONS

For the initial phases of SRB research, when pilot studies will predominate, access to available data holdings can be improved by:

- (1) Creation of a central catalog of relevant data to SRB which will include a record of specially collected SRB pilot data sets and analysis products.
- (2) Transmission of processed and formatted pilot study data sets for specific activities to a central SRB archive.
- (3) Taking advantage of other ongoing data collection/analysis efforts (e.g., ERBE, ISCCP, FIRE, FIFE, TOGA, etc.) to obtain suitable pilot study data sets.

SECTION 6

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Robert A. Schiffer
Workshop Convener

George Ohring and J. Tim Suttles
Cochairmen

SECTION 7

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APPENDIX A

LIST OF PARTICIPANTS

1. Organized into Panels
2. Addresses and Telephone Numbers

LIST OF PARTICIPANTS

1. Organized into Panels

NASA and WCRP REPRESENTATIVE: R.A. Schiffer
IAMAP REPRESENTATIVE: T. Vonder Haar
COCHAIRMEN: G. Ohring and J. T. Suttles

PANEL 1—SCIENTIFIC NEEDS AND APPLICATIONS

Chairman: V. Ramanathan
Vice Chairman: S. Warren

Members: J. Hansen
R. Reck
P. Sellers
A. Slingo
A. Lacis
Harshvardhan

PANEL 2—OBSERVATIONS AND ANALYSIS

Cochairmen: E. Raschke and T. Vonder Haar
Vice Chairman: K. Hanson

Members: M.-D. Chou
W. Darnell
Y. Fouquart
J. Hay
R. Kandel
G. Major
G. Stephens
D. Tarpley

PANEL 3—CALIBRATION AND VALIDATION

Chairman: H. Grassl
Vice Chairman: J. Deluisi

Members: A. Arking
R. Ellingson
C. Fröhlich
F. Kasten
G. Kukla
R. Pinker
J. Schmetz
C. Whitlock
W. Wiscombe
R. Frouin

PANEL 4—DATA SETS DEVELOPMENT

Chairman: C. Gautier
Vice Chairman: P. Taylor

Members: B. Barkstrom
C. Justus
K. Katsaros
W. Rossow
S. Vemury
A. Gruber

LIST OF PARTICIPANTS

2. Addresses and Telephone Numbers

Dr. Albert Arking
NASA Goddard Space Flight Center
Code 915
Greenbelt, MD 20771
301/344-7208

Dr. Bruce R. Barkstrom
NASA Langley Research Center
Mail Stop 420
Hampton, VA 23665
804/865-2977

Dr. Ming-Dah Chou
NASA Goddard Space Flight Center
Laboratory for Atmospheres, Code 613
Greenbelt, MD 20771
301/344-8499

Wayne L. Darnell
NASA Langley Research Center
Mail Stop 420
Hampton, VA 23665
804/865-2977

Dr. Adarsh Deepak
Science and Technology Corporation
101 Research Drive
Hampton, VA 23666
804/865-1894

Dr. John DeLuisi
NOAA/ERL
325 Broadway
Boulder, CO 80303
303/497-6824

Prof. Robert G. Ellingson
University of Maryland
Department of Meteorology
College Park, MD 20742
301/454-5088

Dr. Yves Fouquart
Université de Lille
Boite postale no 36
Lab d'Optique Atmospherique
59655 Villeneuve d'Ascq Cedex
FRANCE
20919222

Dr. Claus Fröhlich
Weltstrahlungszentrum
Physikalisch-Meteorologisches Observatorium
Postfach 173
CH-7260 Davos Dorf
SWITZERLAND
0041/83/52131

Dr. Robert J. Frouin
Scripps Institution of Oceanography
California Space Institute
Code A-021
La Jolla, CA 92093
619/452-6243

Dr. Catherine Gautier
Scripps Institution of Oceanography
California Space Institute
Code A-021
La Jolla, CA 92093
619/452-4936

Prof. Hartmut Grassl
Postfach 1160
GKSS-Forschungszentrum
D-2054 Geesthacht
FEDERAL REPUBLIC OF GERMANY
04152/12567

Dr. Arnold Gruber
NOAA/NESDIS E/RA11
Suitland Professional Center
Washington, DC 20233
301/763-4290

Dr. James Hansen
NASA Goddard Institute for Space Studies
2880 Broadway
New York, NY 10025
212/678-5619

Dr. Kirby Hanson
NOAA
4301 Rickenbacker Causeway
Miami, FL 33149
305/361-4372

Dr. Harshvardhan
NASA Goddard Space Flight Center
Code 613
Greenbelt, MD 20771
301/344-8805

Dr. John Hay
University of British Columbia
Department of Geography
Vancouver, BC
CANADA V6T 1W5
604/228-4929

Dr. Garry E. Hunt*
Centre for Remote Sensing
Imperial College
London, SW7 2BZ
UNITED KINGDOM
01-589 5111 Ext. 6691

Dr. C. G. Justus
Georgia Tech
School of Geo. Sci.
Atlanta, GA 30332
404/894-3890

Dr. Robert S. Kandel
Laboratoire de Meteorologie Dynamique
du C.N.R.S.
Ecole Polytechnique
F-91128 Palaiseau Cedex
FRANCE
(6) 941-8200

Dr. Fritz Kasten
Deutscher Wetterdienst
Meteorologisches Observatorium Hamburg
Frahmredder 95
D-2000 Hamburg 65
FEDERAL REPUBLIC OF GERMANY
601/79/24

Prof. Kristina B. Katsaros
University of Washington
Department of Atmospheric Science AK-40
Seattle, WA 98195
206/543-1203

Dr. George Kukla
Lamont Observatory
Palisades, NY 10964
914/359-2900

Dr. Andrew Lacis
Goddard Institute for Space Studies
2880 Broadway
New York, NY 10025
212/866-9599

Dr. James D. Lawrence
NASA Langley Research Center
Mail Stop 401
Hampton, VA 23665

Dr. Gy Major
Institute for Atmospheric Physics
P.O. Box No. 39
Budapest H-1675
HUNGARY
585-711

Dr. George Ohring
NOAA/NESDIS
Climate & Earth Sciences Lab (E/RAI)
Suitland Professional Center, Rm 318
Washington, DC 20233
301/763-4248

Prof. Rachel T. Pinker
University of Maryland
Department of Meteorology
College Park, MD 20742
301/454-5092

Dr. V. Ramanathan
NCAR
1850 Table Mesa Drive
Boulder, CO 80303
303/497-1348

Dr. Ehrhard Raschke
University of Koln
Institute of Geophysics and Meteorology
Kerpener Strasse 13
5000 Koln 41
FEDERAL REPUBLIC OF GERMANY
49-221-470-3682

Dr. Ruth Reck
General Motors Research Labs
Physics Department
Warren, MI 48090
313/575-2946

Dr. William B. Rossow
NASA Goddard Institute for Space Studies
2880 Broadway
New York, NY 10025
212/678-5567

*Authored position paper but was unable to attend the Workshop.

Dr. Robert A. Schiffer
NASA Headquarters
Code EE-8, Rm 139
Washington, DC 20546
202/453-1680

Dr. Johannes Schmetz
ESA/ESOC Meteosat Exploitation Project
Robert-Bosch-Strasse 5
6100 Darmstadt
FEDERAL REPUBLIC OF GERMANY

Dr. P. J. Sellers
NASA Goddard Space Flight Center
Code 624
Greenbelt, MD 20771
301/344-5084

Dr. A. Slingo
Meteorological Office
London Road
Bracknell
Berkshire, RG12 2SZ
ENGLAND
420242

Dr. Graeme L. Stephens
Colorado State University
Department of Atmospheric Sciences
Fort Collins, CO 80523
303/491-8541

Dr. J. T. Suttles
NASA Langley Research Center
Mail Stop 420
Hampton, VA 23665
804/865-2977

Dr. Dan Tarpley
NOAA/NESDIS
Suitland Professional Center
Washington, DC 20233
301/763-4240

Dr. Peter K. Taylor
Inst. of Oceanographic Sciences
Wormley
Godalming
Surrey GU8 5UB
ENGLAND
042879-4141

Dr. Sastri Vemury
Science and Technology Corporation
Maryland Trade Center II
7474 Greenway Center Drive
Greenbelt, MD 20770
301/474-5595

Prof. Thomas H. Vonder Haar
Colorado State University
CIRA/615
Foothills Campus
Fort Collins, CO 80523
303/491-8448

Prof. Stephen Warren
University of Washington
Department of Atmospheric Sciences
AK-40
Seattle, WA 98195
206/543-7230

Dr. Charles H. Whitlock
NASA Langley Research Center
Mail Stop 420
Hampton, VA 23665
804/865-2977

Dr. Warren Wiscombe
NASA Goddard Space Flight Center
Code 613
Greenbelt, MD 20771
301/344-4977

APPENDIX B

POSITION PAPERS

Panel 1

**Scientific Use of Surface Radiation Budget Data
for Climate Studies**

Panel 2

**Surface Radiation Budget
Observations and Analysis**

Panel 3

**Surface Radiation Budget
Calibration and Validation Activities**

Panel 4

**Surface Radiation Budget
Data Sets Development**

SCIENTIFIC USE OF SURFACE RADIATION BUDGET DATA
FOR CLIMATE STUDIES

V. Ramanathan

National Center for Atmospheric Research¹
Boulder, Colorado 80307

Position Paper for

Panel 1
Workshop on Surface Radiation Budget
for Climate Applications
Columbia Inn, Columbia, MD
17-21 June 1985

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1. INTRODUCTION

Surface radiation budget (SRB) is gradually being perceived as an important climate parameter. This increased perception of the importance of SRB for climate studies can be gleaned from recent scientific reports, some of which are cited below:

- The Tropical Ocean and Global Atmosphere (TOGA) program, which seeks to “study the interaction of the tropical oceans and the global atmosphere over a ten year period” (WCP-92), lists the acquisition of the surface radiation budget as an important part of TOGA (WCP-92, 1984).
- The World Ocean Circulation Experiment (WOCE), which is an international program in the planning stages, identifies the determination of the large-scale surface heat fluxes (sum of the net radiation, sensible, and latent heat fluxes) as one of its principal goals (WCP-81, 1984) since the heat flux between the ocean and atmosphere is a central variable in the climate system (also see Bretherton, 1984, for a further elaboration of this point).
- The World Climate Research Program (WCRP) regards the determination of the net surface radiation flux as a high priority research task since it governs the total release of latent and sensible heat from the surface into the atmosphere (WCRP, 1983). Over land surfaces, the principles of radiative and other energy balance terms determine the surface temperature, and the rate of evapotranspiration as well as surface-atmosphere exchange of energy (see Dickinson, 1983, for a more detailed discussion).
- On a more fundamental level, a recent international study, “The Intercomparison of Radiation Codes in Climate Models (ICRCCM),” uncovered significant differences of the order of 30 to 60 Wm^{-2} in the computed surface longwave flux between various radiation codes; and the ICRCCM study strongly recommended field programs to measure surface and atmosphere radiation fluxes to help resolve the source of major uncertainties and errors in the present state-of-the-art radiation codes (WCP-93, 1984).

The above examples illustrate the potential use of surface radiation budget in a complex array of geophysical problems involving ocean-atmosphere interactions, ocean circulation, land-atmosphere interactions, and validation of radiation schemes used in climate models. Another potentially important area (of use for SRB) concerns climate change due to CO_2 and other trace gases. Climate model simulations (results will be shown later) suggest that, because of feedbacks involving H_2O and ice-albedo, major perturbations to surface radiation fluxes will accompany the warming induced by the greenhouse effect.

While the scientific need for SRB is very strong, it has not found much quantitative use in climate studies. The principal reason for the lack of interest in SRB is that the quality of the available SRB climatology is largely unknown. For example, available maps of SRB over oceans (e.g., Esbensen and Kushnir, 1981) are based on empirical expressions that employ observed meteorological data (cloud cover, temperature, and humidity) to infer the radiation budget. The validity of the expressions for the global oceans as well as the accuracy of the data (for cloud cover and humidity) have not been carefully documented. Furthermore, long-term SRB measurements over the oceans are rare (WCP-92, 1984), and hence validation of the traditional approach of employing empirical expressions (e.g., see pages 13 and 14 of Esbensen and Kushnir, 1981) has proved to be extremely difficult. Over the land, however, surface network of long-term (1 year to a decade) solar flux measurements are available for many stations (Jenne and McKee, 1985) including over the Antarctic (e.g., Yamanouchi, 1984). The available surface measurements, in spite of their potential value, have not exerted much influence in theoretical or modeling studies of climate. Perhaps the available data may find increased use, if rigorous statistical attempts are made to relate the point-source pyranometer measurements to the spatial averages required for model studies. However, comparisons over selected ocean weather stations indicate significant discrepancies between various

empirical expressions (Smith and Dobson, 1984). For example, at one ocean weather station, the long-term heat loss is estimated to be 28 Wm^{-2} by Smith and Dobson whereas for this station the empirical expressions of the sort used by Esbensen and Kushnir (1981) would have yielded a value of about 98 Wm^{-2} (also see Smith and Dobson, 1984).

In view of the above mentioned deficiencies in the traditional approaches for obtaining SRB, recent studies (e.g., Gautier, 1984; Dedieu et al., 1984; also see the summary in WCP-92, 1984) are attempting a new approach that involves the use of satellite radiances to infer surface radiation fluxes. Surface measurements still play a key role (in the new approach) since these are either used to correlate top-of-the-atmosphere radiances with surface fluxes (e.g., Gautier et al., 1980; Gautier, 1984) or used as ground truth to validate satellite inferred values (see page 24 in WCP-92, 1984).

Although satellite radiance measurements offer a potentially viable approach, numerous theoretical and observational issues have to be addressed before the satellite approach can be adopted for obtaining SRB. The theoretical issues include: the information content of top-of-the-atmosphere (TOA) radiances with regard to surface fluxes; the dependence of the correlation between TOA radiances and SRB (assuming the existence of such correlations) on location, diurnal cycle, season, and on satellite viewing geometry; and spectral narrowband versus broadband fluxes. Important observational issues include: spatial and temporal sampling considerations; the maintenance and necessity of long-term ground truth measurements over the ocean and land; the interpretation of ground truth point-source measurements in terms of spatially averaged information contained in satellite radiances; and, finally, if the correlation between TOA and SRB involves parameters such as clouds and humidity, then the scope of the observational issues broadens significantly to that of determining the correlation parameters to sufficient accuracy.

I will address some of the above issues in the ensuing discussions. As far as possible, the discussions will make use of the available literature but quantitative observational information is scarce. Hence, we will largely rely on computations based on radiation models and general circulation models (GCMs) to characterize the statistics of SRB and its relation to TOA fluxes. It is hoped that these discussions will aid in the process of articulating an effective strategy for determining global distributions of SRB.

The discussions will focus next on the potential scientific uses of SRB, which include: validation of general circulation models; heat flux boundary condition for ocean studies; the role of clouds in surface and atmospheric radiative heating; and long-term climate trends.

2. SURFACE RADIATION BUDGET CHARACTERISTICS

2.1 Summary of Satellite Studies of SRB

Comparison of satellite radiances with surface measurements of radiative fluxes reveals encouraging similarities with respect to solar fluxes (e.g., see WCP-92, 1984). As a result, several studies (Raschke and Preuss, 1979; Gautier et al., 1980; Tarpley, 1979; and Dedieu et al., 1984) have attempted to infer net solar flux at the surface from narrowband satellite radiances. Figure 1 taken from the summary article in WCP-92 (1984) shows a comparison between satellite estimates and pyranometer measurements of daily average net solar flux at the surface. The rms difference between the two estimates is about 15 Wm^{-2} . With current technology, it is perhaps difficult to improve upon the rms difference of 15 Wm^{-2} , particularly since the magnitude of the instrument and spatial sampling error in the pyranometer measurement is expected to be of the order of 10 Wm^{-2} (WCP-92, 1984). Further progress depends on several factors including the following: a better theoretical understanding of the relationship between TOA and surface fluxes; a better understanding of the statistics of the variations (daily and monthly) in the surface fluxes and its relationship to TOA fluxes;

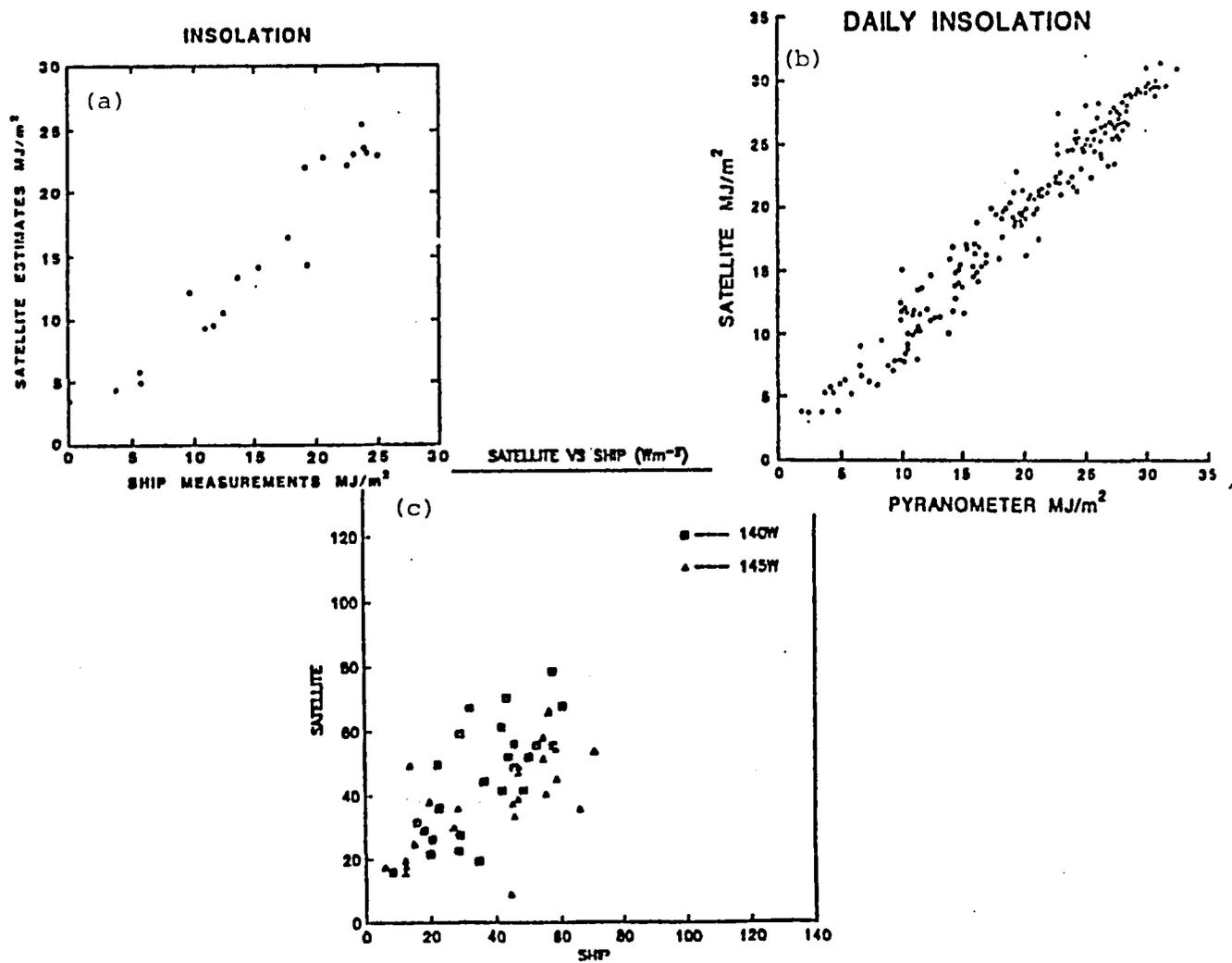


Figure 1. Intercomparison of net shortwave radiation estimates from GOES with in situ pyranometer measurements over (a) the tropical Atlantic Ocean during GATE, (b) southeastern Canada, (c) the northeast Pacific Ocean during STREX. The measurements have been averaged over 24 hours. Source: WCP-92, 1984.

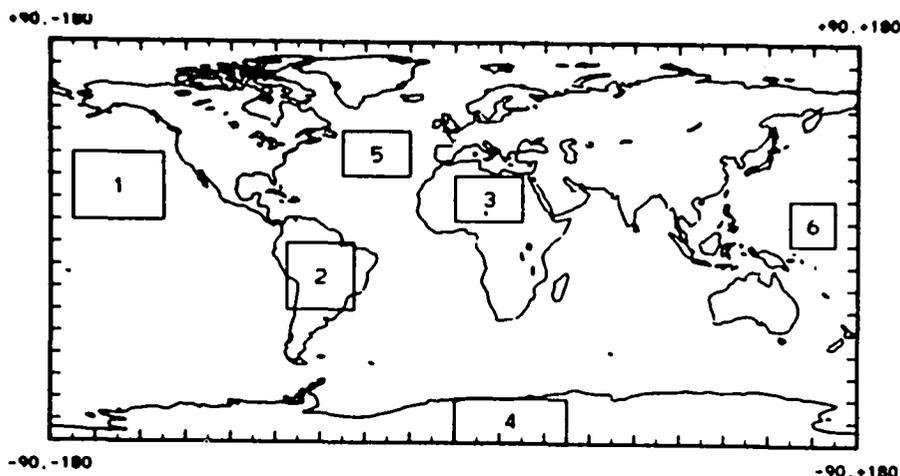


Figure 2. Model regions adopted for the analyses shown in Figures 3 to 6. The adopted regions are indicated by blocks numbered 1 to 6. The model resolution is about 4.5° lat \times 7.5° long. Each of the regions has about 20 grid points.

current approaches employ narrowband radiances (from GOES or other satellites) and we need studies that will elucidate the factors that govern the relationship between narrowband and broadband fluxes; and availability of quantitative studies of the accuracies and representativeness of surface measurements. Furthermore, current satellite studies are focusing primarily on solar fluxes and place relatively minimal emphasis on obtaining longwave fluxes.

In what follows, we provide information on the above issues based on model computations. The regional distribution of the solar and longwave fluxes as well as their statistical distributions are obtained from the NCAR community climate model (Pitcher et al., 1983, and Ramanathan et al., 1983), which is a spectral general circulation model (GCM). For the purposes of this study, several improvements were incorporated in the GCM including the following: an improved H_2O radiation scheme that accounts for H_2O continuum absorption; and additional upper tropospheric layers to account for the radiative effects of cirrus clouds. The current model has 12 layers in the vertical as opposed to the nine layers in the earlier GCM; a liquid-water scaled cirrus emissivity scheme. In addition to showing global distributions, we show results for specific regions and these specific regions (six of them) are enclosed by boxes in Figure 2. Each of these boxes contains about 20 model grid points. The resolution of each grid point is 4.5° lat \times 7.5° long.

2.2 TOA Versus Surface Fluxes: Instantaneous Values and Monthly Means

The model radiation budget is sampled once in 12 hours and these values are referred to as instantaneous values. For the six regions shown in Figure 2, the absorbed solar radiation for the surface-atmosphere system (SABTP) is plotted against the absorbed solar radiation for the surface alone (FRSA) in Figure 3. SABTP and FRSA are also equal to the net (down-up) downward flux at TOA and at the surface respectively. Monthly mean values are plotted in Figure 3a whereas instantaneous values (sampled twice daily) are plotted in Figure 3b. Irrespective of the sampling interval, the TOA

SABTP: Absorbed Solar by Surface + Atmosphere;
FRSA: Absorbed Solar by Surface

(a) Monthly Mean

(b) Instantaneous Values

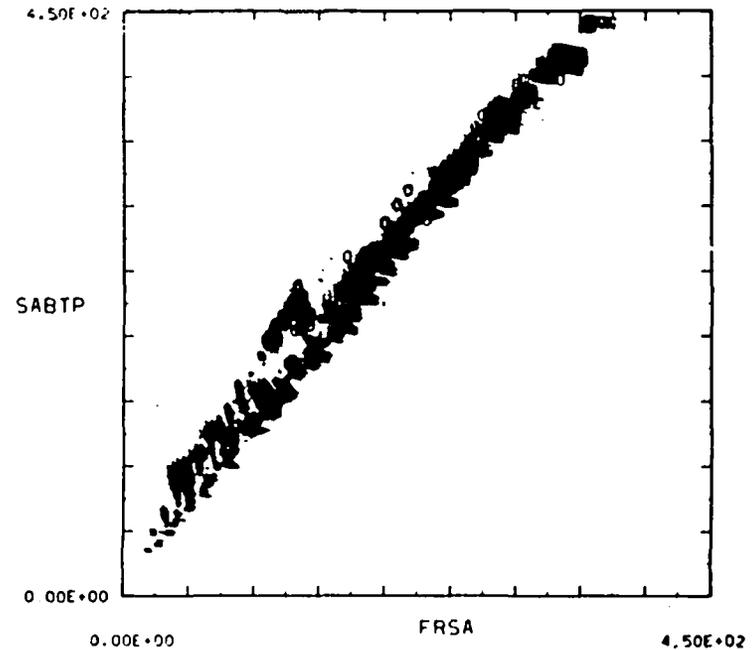
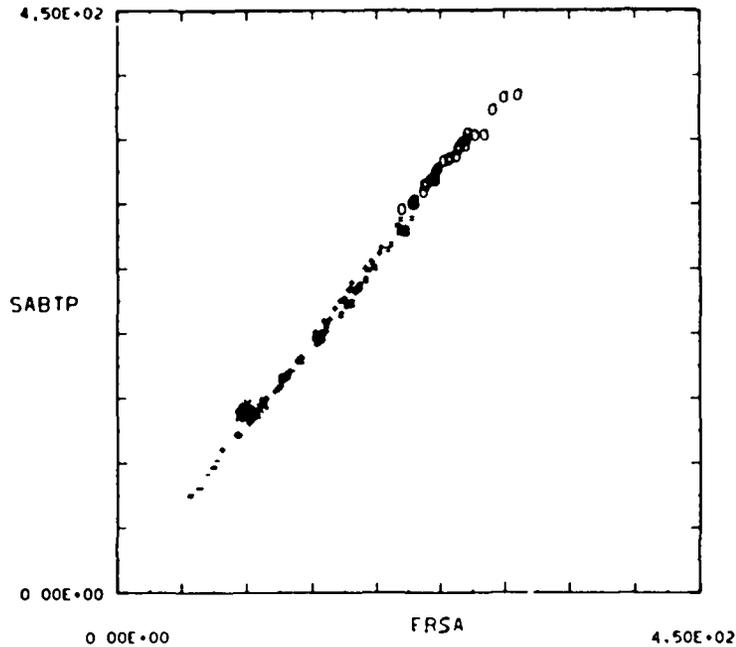


Figure 3. Scatter plots of top-of-the atmosphere (TOA) and surface fluxes of absorbed solar radiation. The results shown in this figure as well as in Figures 7 to 9 are obtained from the NCAR general circulation model simulations. For the results shown in the study, the model was run with prescribed sea-surface temperature and with perpetual January boundary conditions. The instantaneous values are obtained by sampling the model output once ever 12 hours. The monthly means are averaged over 60 samples.

and surface solar fluxes are correlated strongly, thus confirming the findings of the observational studies. Furthermore, temporal averaging reduces the “noise” considerably. The reasons for the strong correlation in the model are as follows: (1) For clear-sky conditions, the column integrated atmospheric absorption is reasonably insensitive to latitude or regional location; for example, poleward decrease in H₂O is adequately compensated by the increase in the optical path due to the poleward increase of $1/\cos\theta$ where θ is the solar zenith angle. Hence H₂O absorption is not subject to a strong poleward decrease. (2) The tropospheric (including clouds) absorption of solar radiation occurs mainly in the IR ($\lambda > 0.9 \mu\text{m}$) and hence the maximum (total, not clouds alone) absorption can only be about 30% or so. Roughly $\frac{2}{3}$ of this 30% is due to absorption by H₂O, CO₂, O₃, and CO₂. Clouds absorb near IR but do so at the expense of H₂O absorption below the clouds since clouds reflect or absorb the solar radiation before it reaches H₂O below the clouds. Because of this compensation between cloud absorption and H₂O absorption, the total absorption (by clouds and gases) is not altered drastically by clouds. The net result is that variations in net flux at TOA are largely manifested as variations in net flux at the surface.

The radiation scheme in the CCM accounts for cloud scattering and absorption in a simplified manner. However, the CCM calculations were repeated by a detailed delta-Eddington scattering code with eight spectral intervals and these calculations revealed the same strong correlation (as shown in Fig. 3) between TOA and surface solar fluxes.

Figure 4 shows scatter plots for TOA and surface longwave fluxes and this figure is drastically different from Figure 3 in that the TOA fluxes bear no resemblance to surface fluxes. Figure 5 shows the instantaneous values for three separate regions and again the TOA-surface flux correlation is very weak, if not nonexistent. Averaging the instantaneous values (Fig. 6) reduces the spread and seems to yield a better correlation but the correlation reveals a strong regional dependence.

In spite of the results shown in Figures 4 and 5, we cannot yet rule out the possibility of obtaining surface longwave fluxes from space. For example, better surface fluxes may be had were one to probe the outgoing longwave fluxes as a function of wavelength (J. Coakley, NCAR, Boulder, Colorado, private communication). Currently, there are few published papers (e.g., Darnell et al., 1983, and Pinker and Corio, 1984) which have made tentative attempts at obtaining surface longwave fluxes (even in cloudy atmospheres) using satellite measurements in conjunction with radiation models. The present results (Figs. 4 and 5) merely illustrate the complexities of the problem and should not be construed as illustrating the hopelessness of obtaining surface longwave fluxes from space.

2.3 TOA Versus Surface Fluxes: Statistics

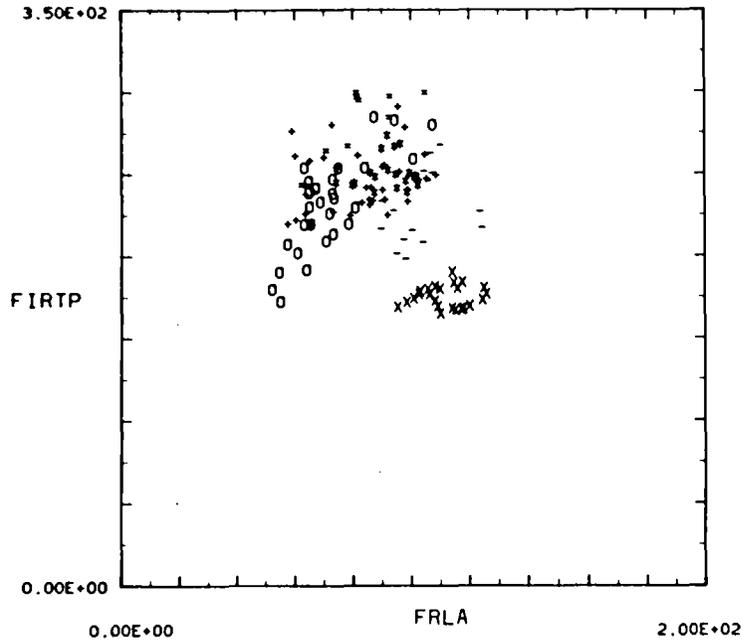
Global distributions of the daily and monthly mean standard deviations of the longwave fluxes are shown in Figure 7. The standard deviations of the instantaneous values (Figs. 7a and 7b) and the monthly mean values (Figs. 7c and 7d) do not reveal any strong similarity between the TOA and surface flux patterns. Indeed, in the equatorial regions there is even an anti-correlation between the two fields. For example, where the standard deviation in TOA fluxes exceeds 60 Wm^{-2} (e.g., the monsoon region over Indonesia), the deviation in surface fluxes is a minimum with values less than 30 Wm^{-2} . The surface minimum is somewhat expected because of the saturation of the H₂O bands (including the continuum band) in the humid tropical regions. The apparent lack of correlation between variations in TOA and surface fluxes also exists for clear-sky fluxes as shown in Figure 8. Although there is very little correlation between TOA and surface fluxes (either for clear skies or cloudy skies), we cannot rule out the possibility of discovering new ways (to process the satellite radiances) that can yield surface longwave fluxes from TOA fluxes.

The instantaneous deviation of instantaneous solar fluxes is shown in Figure 9. As to be expected from Figure 3, the patterns of TOA and surface flux deviations are quite similar. Together,

FIRTP: Outgoing Longwave Flux at Top-of-the-Atmosphere (TOA);
FRLA: Net (Up-Down) Longwave Flux at the Surface

Monthly Mean Values

- ♦ SUB-TROPICAL NORTH PACIFIC
- SAHARA DESERT AFRICA
- NORTH ATLANTIC



Instantaneous Values

- o AMAZON BASIN
- x ANTARCTIC PLATEAU
- = EQUATORIAL PACIFIC

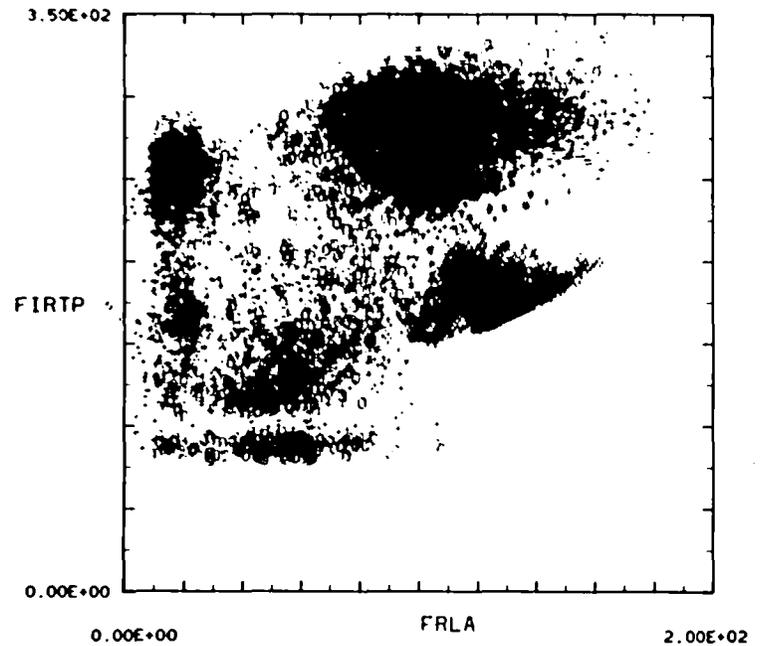


Figure 4. As in Figure 3, but for longwave fluxes. Refer to Figure 3 for explanation of the model calculations.

FIRTP: Outgoing Flux at TOA; FRLA: Net Up Flux at Surface

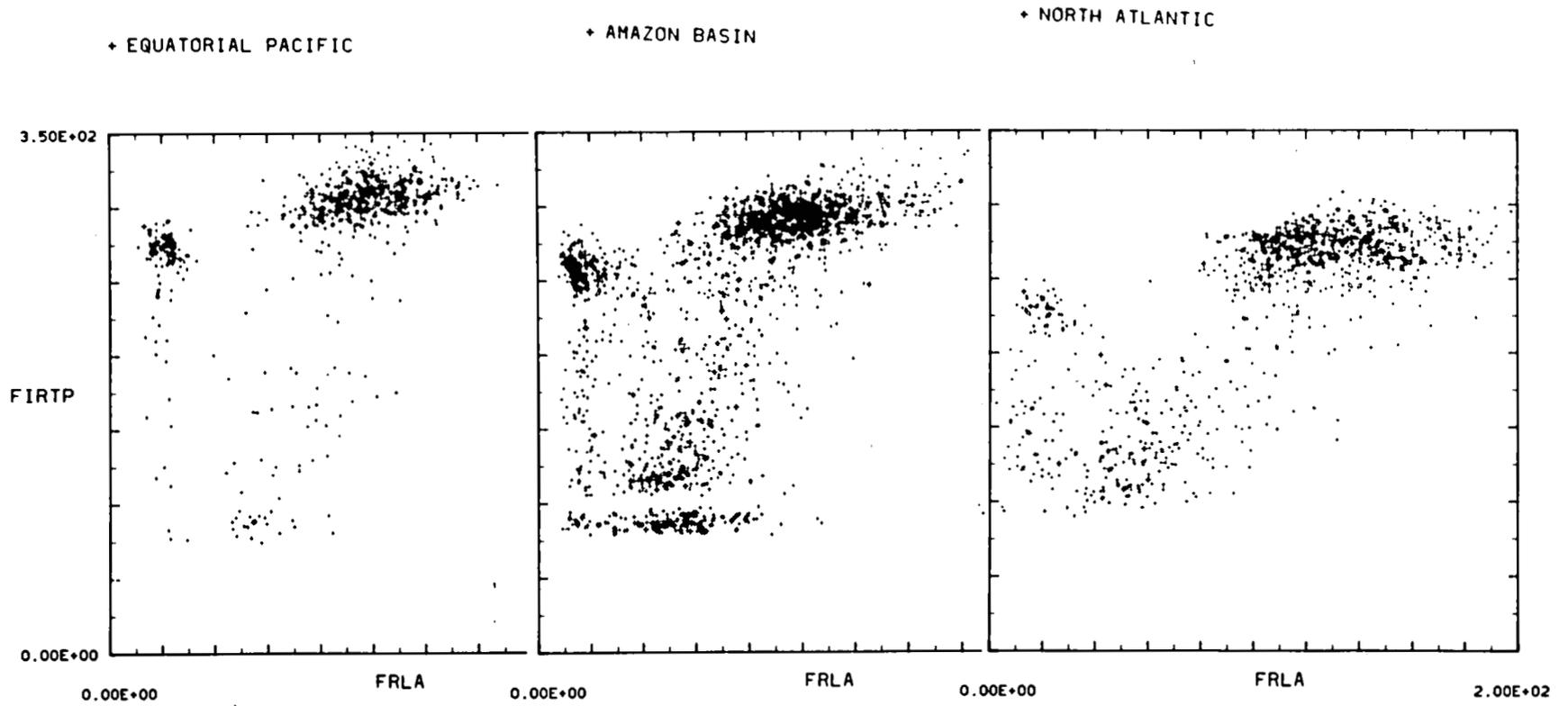


Figure 5. As in Figure 3, but for instantaneous longwave fluxes plotted for specific regions.

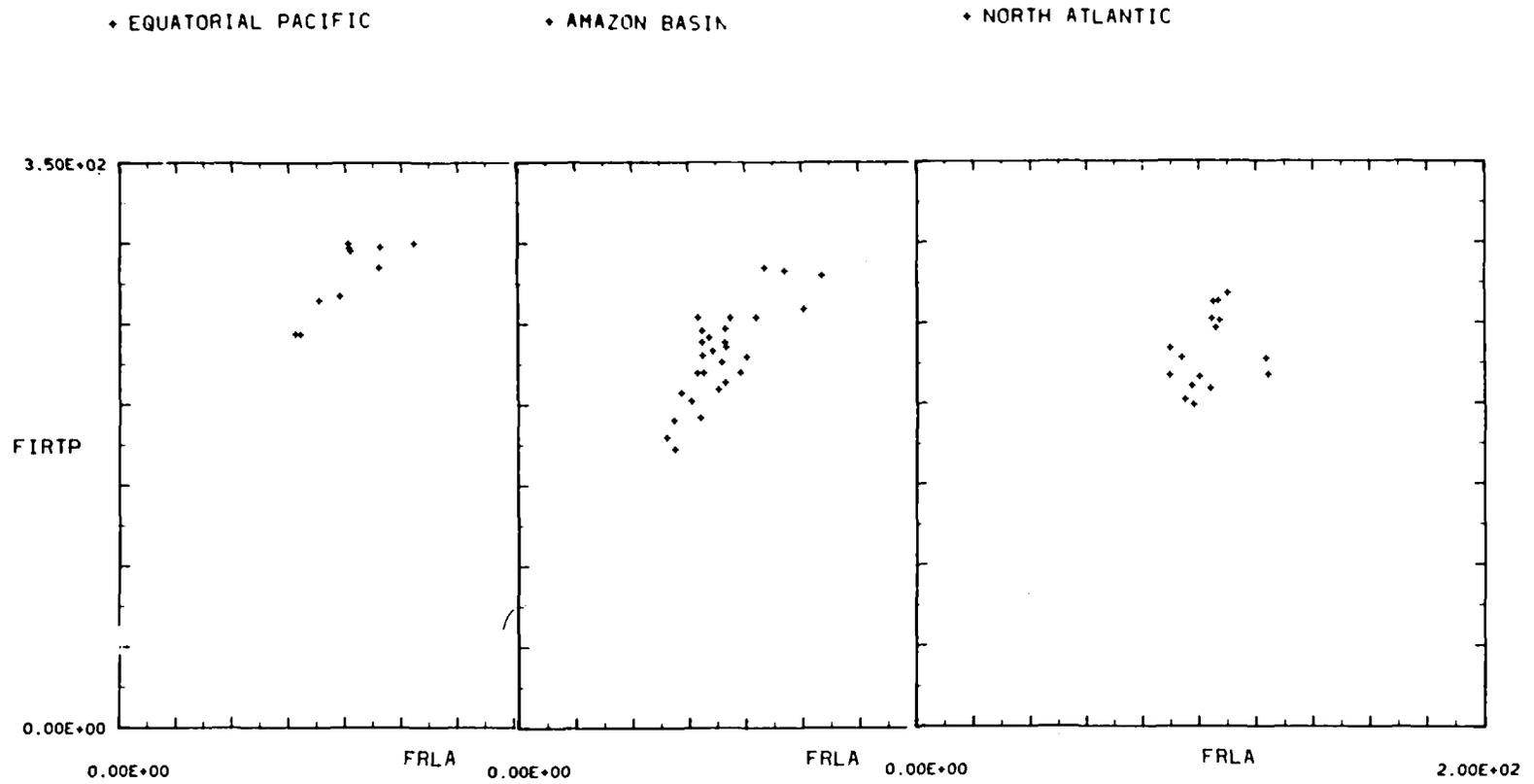


Figure 6. As in Figure 3, but for monthly mean longwave fluxes for specific regions.

DAILY STANDARD DEVIATION OF LONGWAVE ($W m^{-2}$)
[GCM Simulations for January]

(a) TOA Flux

(b) Net Surface Flux

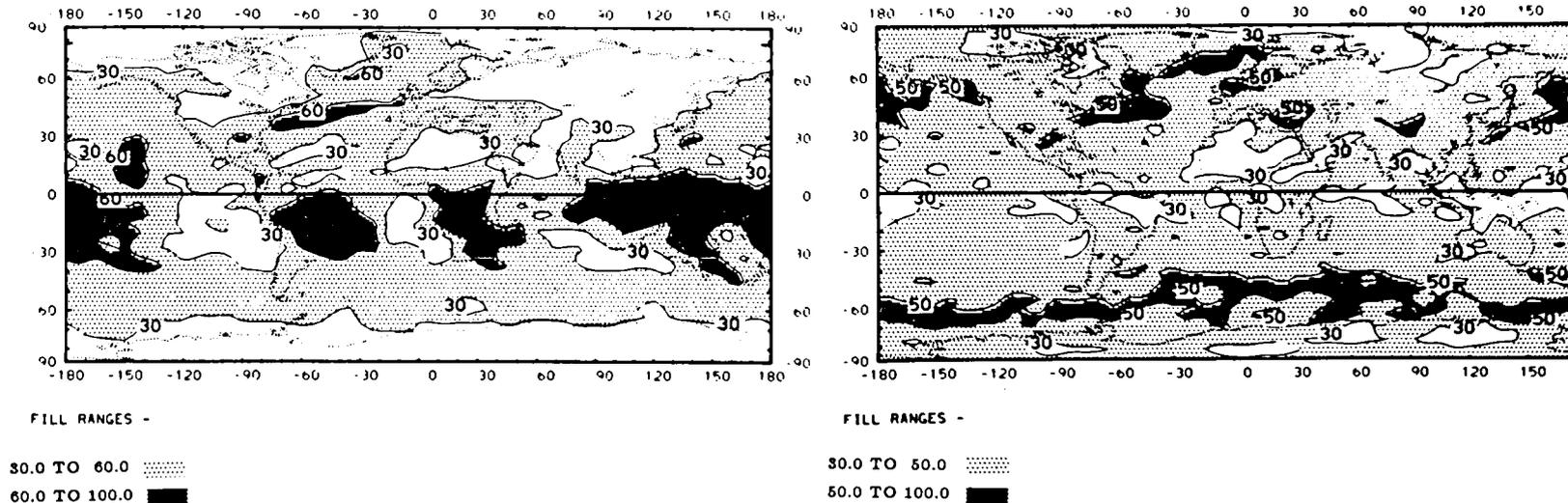
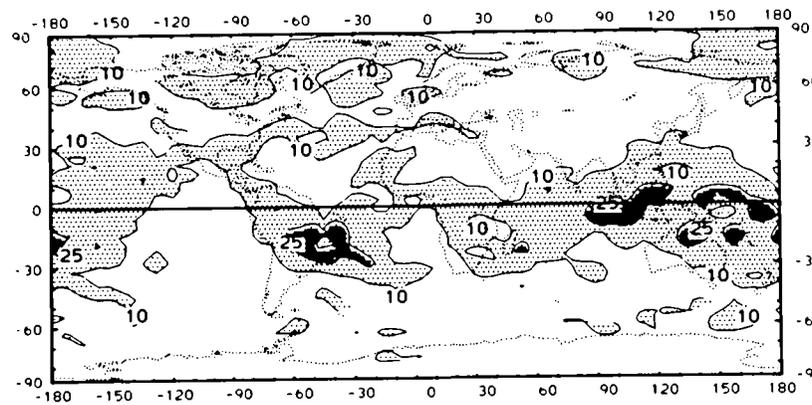


Figure 7. Standard deviations of GCM longwave fluxes (also see Fig. 3). (a) and (b) Daily deviation of TOA and surface net fluxes; (c) and (d) monthly mean deviation of TOA and surface net fluxes. The deviation was estimated from four monthly means and an interval of 20 days was given between each sample.

MONTHLY STANDARD DEVIATION OF LONGWAVE FLUX ($W m^{-2}$)
 [GCM Simulation for January]

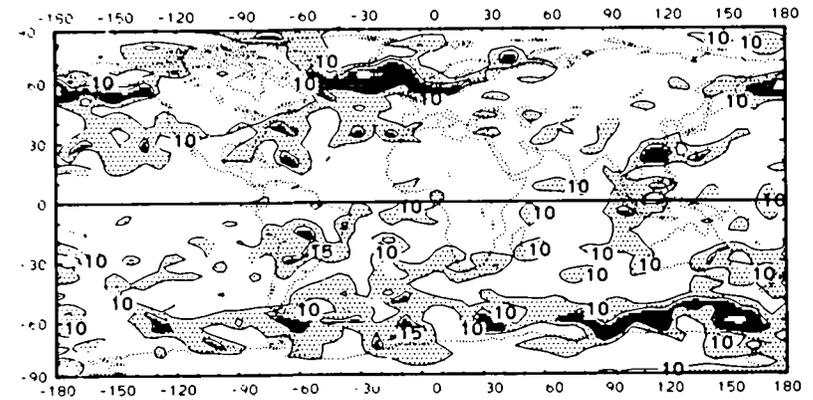
(c) TOA Flux



FILL RANGES -

10.0 TO 25.0 
 25.0 TO 40.0 

(d) Net Surface Flux

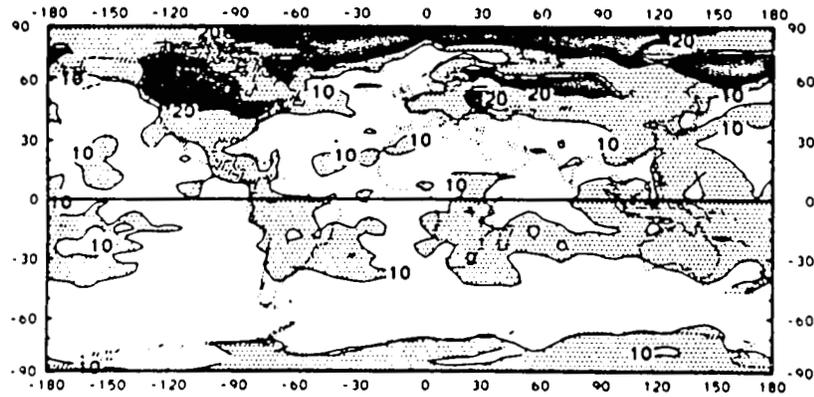


FILL RANGES -

10.0 TO 15.0 
 15.0 TO 25.0 

(a) TOA

TOA CLR LWV STN DV 30 DAYS (AT 12 HRS)



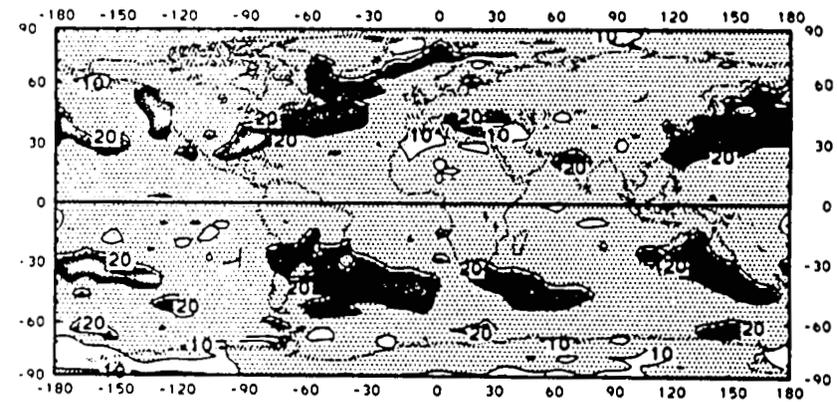
FILL RANGES -

10.0 TO 20.0

20.0 TO 40.0

(b) Surface

SUR CLR LWV STN DV 30 DAYS (AT 12 HRS)



FILL RANGES -

10.0 TO 20.0

20.0 TO 40.0

Figure 8. Same as Figure 7, but for daily clear-sky longwave fluxes.

MONTHLY MEAN STANDARD DEVIATION: ABSORBED SOLAR RADIATION ($W \cdot m^{-2}$)

TOA: Surface + Atmosphere

Surface

TOA SOL ABS STN DV 30 DAYS (AT 12 HRS)

SUR SOL ABS STN DV 30 DAYS (AT 12 HRS)

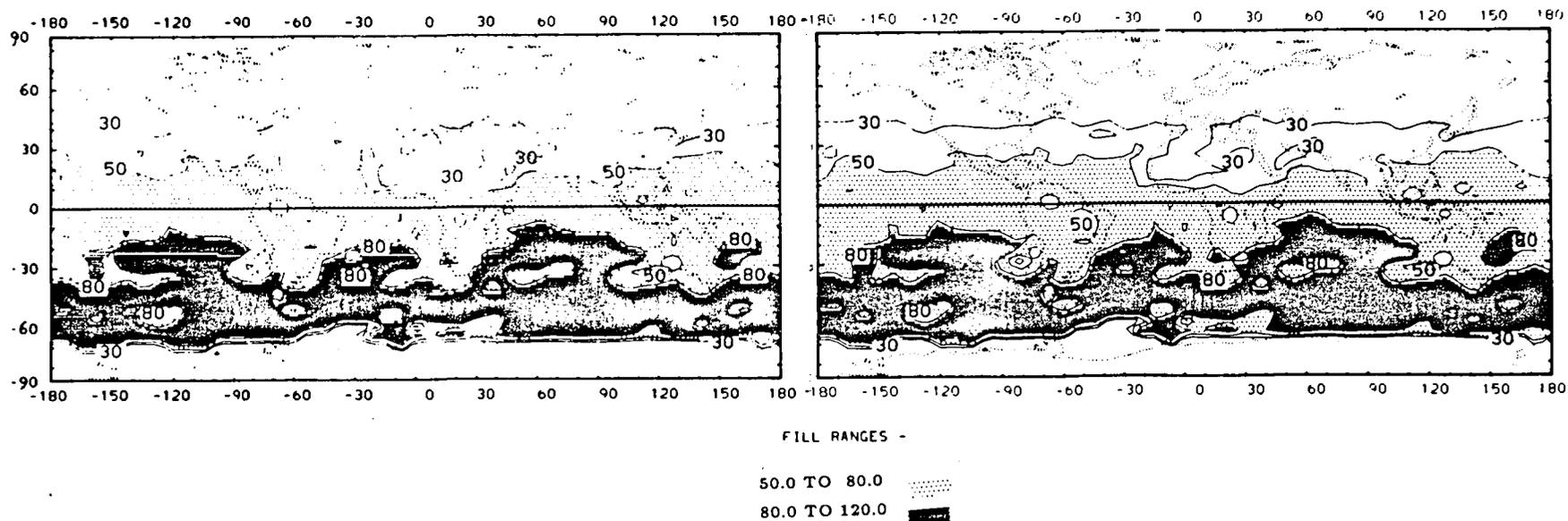


Figure 9. Monthly mean standard deviation of absorbed solar fluxes. See Figure 7 for sampling strategy for estimating the monthly deviation.

Figures 3 and 9 confirm the basic finding of the observational studies that the information content in satellite radiances is sufficient to infer surface fluxes of solar radiation.

2.4 Surface Longwave Fluxes: Modeling Approaches

There have been attempts to employ satellite retrieved temperature and humidity soundings in radiation models to compute longwave fluxes (see pages 27 to 28 of WCP-92, 1984; see also Darnell et al., 1983; and Pinker and Corio, 1984). There have also been attempts to employ statistical linear regression analyses to relate narrowband radiances directly to surface fluxes (see the reference to Smith's unpublished study in WCP-92, 1984). As yet, the results of these studies are inconclusive.

Another alternative is to use long-term (1 to 2 years) measurements of surface fluxes to validate radiation models and subsequently employ the models for estimating surface fluxes. For clear-sky conditions, measured and computed longwave fluxes agree within 20 Wm^{-2} (e.g., see Figs. 10 to 12 of ICRCM, 1984). For example, comparison of monthly mean surface longwave flux observed at the Mizuho Station (70° ; an Antarctic station) with calculated values shows a reasonable degree of agreement (see Fig. 10, adopted from Yamanouchi, 1984). However, the Yamanouchi study employs broadband models to treat the radiative effects of H_2O and CO_2 . For a more rigorous test of the theory, the Yamanouchi study should be repeated with line-by-line or narrowband calculations and should include more surface stations representative of land and ocean areas in low to mid-latitude regions. Furthermore, as concluded by the ICRCM (1984) study, the errors in broadband flux measurements are too large ($\pm 5\%$ or larger; see page 22 of ICRCM, 1984) for incisive validation of models. As recommended by the ICRCM (1984) study, we need narrow and broadband radiance (intensity) measurements since the instrumental accuracy of the radiance measurements is of the order of $\pm 1\%$.

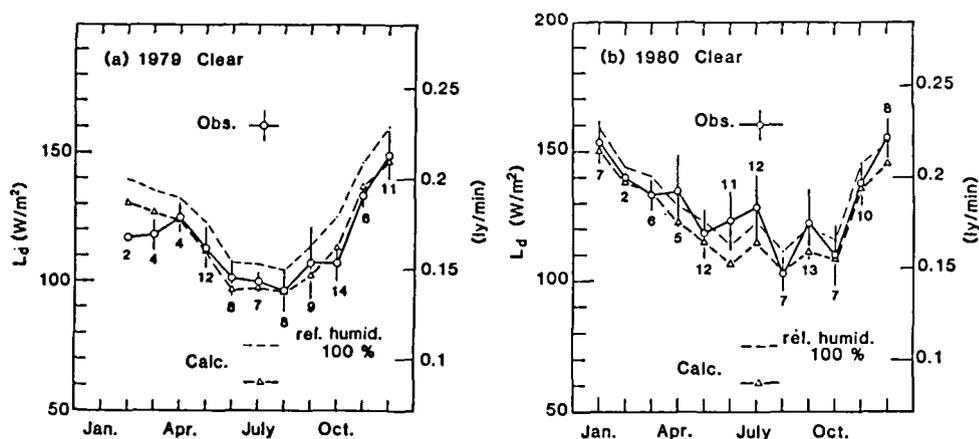


Figure 10. Comparison of calculated and measured downward longwave radiation fluxes (L_d) for a clear sky at Mizuho Station, Antarctica, in 1979. The thick broken line with triangles shows calculations for the same conditions as the measurements, and the thin broken line represents calculations for 100% relative humidity in the troposphere with other parameters remaining constant. Vertical bars for measured points are standard deviations of measurements. Numbers in the figure indicate the number of clear days ($n < 1/10$) in each month. (Source: Yamanouchi, 1984.)

2.5 Narrowband to Broadband Radiances

The operational instruments on satellites measure narrowband radiances. The conversion of these radiances to broadband fluxes either at the surface or at the TOA is beset with numerous difficulties. Modeling and empirical studies are needed to pin down the various factors that govern the spectral distribution of TOA radiances and to infer the parameters that determine the narrowband to broadband conversion.

In order to illustrate the nature of the problem, we discuss below the spectral dependence of the clear-sky ocean and land reflectivities. Radiative transfer model calculations (Tanaka and Nakajima, 1977) for TOA and surface reflectivity over the ocean are shown in Figure 11. The decrease in TOA reflectivity with increasing wavelength (see the right panel of Fig. 11a and the upper portion of Fig. 11b) can largely be understood from the wavelength dependence of Rayleigh optical depth. However, the spectral dependence of the surface reflectivity is governed largely by the interaction of the relative fraction of the direct and scattered solar beam with the zenith angle dependence of the surface reflectivity. The net effect of this interaction is such that the slope of the spectral dependence of ocean surface reflectivity changes in magnitude and in sign with a change in the solar zenith angle (compare Fig. 11a first panel with Fig. 11b). The fundamental implication of Figure 11 is that, even for as simple a case as clear-sky ocean, the narrowband to broadband correlation is a complicated function of zenith angle and other factors such as hydrosols (compare the various curves numbered 1 to 10 in Fig. 11; these curves differ only in the assumed hydrosol concentration).

Clear-sky reflectivities over the land also show complicated behavior. Most of the complication arises due to the spectral dependence of vegetation reflectivities (Dickinson, 1983). For example, model calculations (Briegleb et al., 1985) which account for the spectral dependence of vegetation reflectivity reveal significant differences between visible (0.5–0.7 μm) and broadband (0.2–4 μm) reflectivities at TOA (see Fig. 12). The differences shown in Figure 12 have important implications to satellite studies since many of the operational instruments have a 0.5–0.7 μm channel which is used to infer planetary broadband albedo (e.g., Gruber and Winston, 1978).

3. SCIENTIFIC USES OF SRB

As mentioned earlier, surface radiation budget (SRB) has important implications for many geophysical problems involving the oceans, the atmosphere, and the land surface. The potential scientific uses of SRB have been discussed in a number of reports (e.g., Bretherton, 1984; WCP-92, 1984; Niiler, 1984; and Raschke and Kondratiev, 1983, to cite just a few). In what follows, I will focus on three key scientific problems in which SRB data can play a unique and fundamental role.

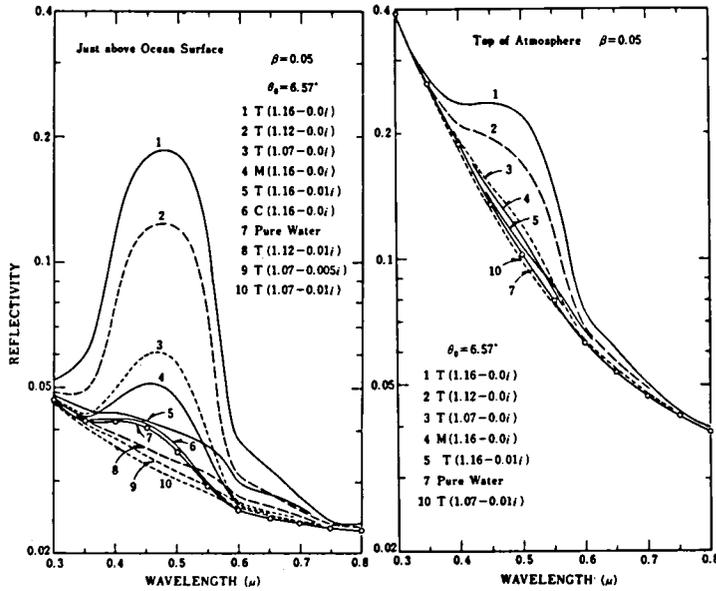
3.1 Cloud-Radiative Forcing of the Troposphere and the Surface

Without any doubt, cloud-radiative interactions are one of the important outstanding atmospheric science problems. Satellite broadband radiation budget measurements can be used to infer the role of clouds in modulating the radiative fluxes to the surface-atmosphere system. This modulating effect can be defined in terms of the cloud-radiative forcing (Charlock and Ramanathan, 1985; and Hartmann et al., 1985) which is defined as follows: If F is the net (up-down) outgoing longwave flux, and if subscripts cl and ov refer respectively to clear-sky and overcast conditions, then for a region covered with fractional cloud cover, C , we have:

$$F = F_{cl}(1 - C) + F_{ov}C \quad (1)$$

$$= F_{cl} - C(F_{cl} - F_{ov}) \quad (2)$$

(a) Solar Zenith Angle: 6.57°



(b) Solar Zenith Angle: 84.7°

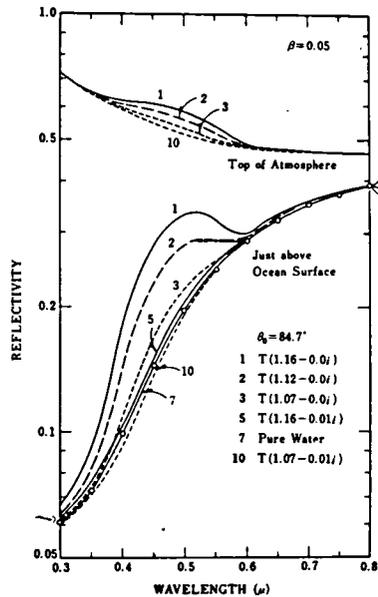


Figure 11. Reflectivities at the top of the atmosphere (upper curves) and just above the ocean surface as functions of wavelength. Letters C, M, and T correspond to the clear, medium turbid, and turbid ocean models, respectively; a number in parentheses indicates the index of refraction of hydrosols. β is atmospheric turbidity. (Source: Tanaka and Nakajima, 1977.)

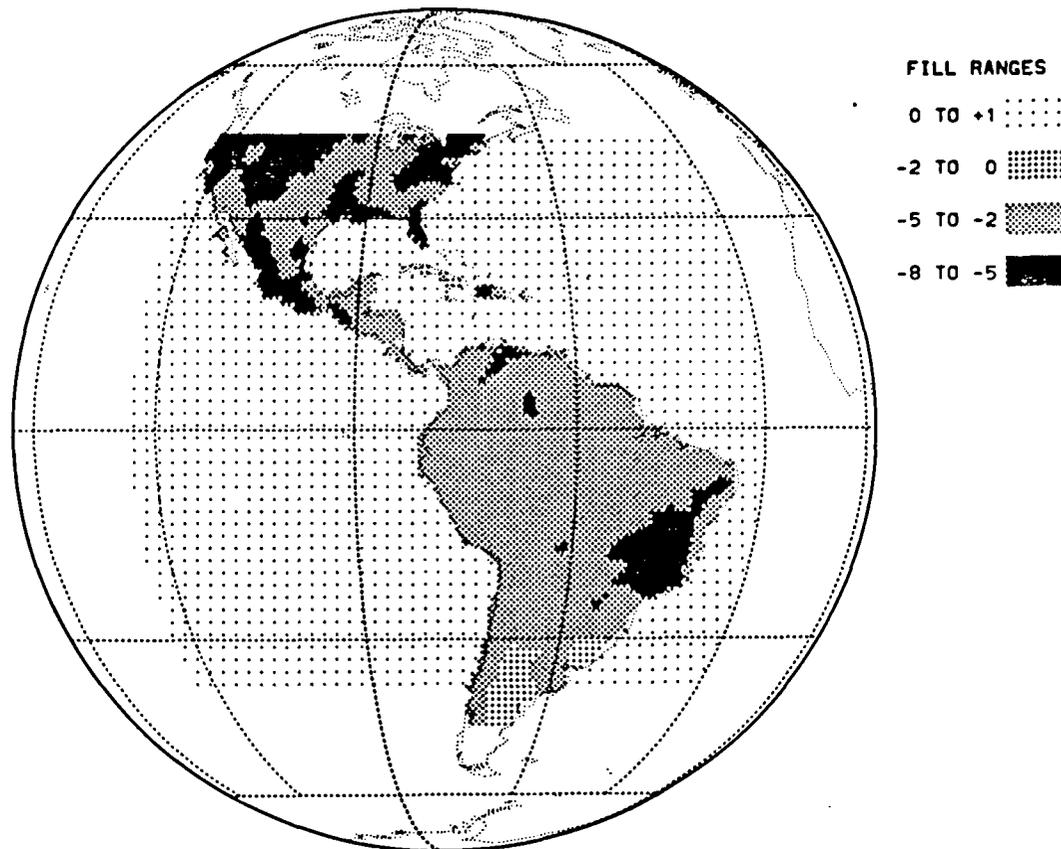


Figure 12. Computed albedo differences (%) between visible (0.5–0.7 μm) and broadband (0.2–0.4 μm) albedo (%) at TOA. The model calculations are for clear-sky, noontime November conditions. (Source: Briegleb et al., 1985.)

$$CF(\text{TOA}) = C(F_d - F_{ov}) \quad (3)$$

and from (2), it follows:

$$CF(\text{TOA}) = F_d - F \quad (4)$$

The definition of (4) applies for any arbitrary configuration of clouds. Thus the cloud forcing is simply the difference between the clear-sky flux and the flux for average cloudy conditions. It is conceptually straightforward to infer F_d from satellite measurements and F (i.e., flux for average cloudy conditions) is routinely measured by satellites. While $CF(\text{TOA})$ is an important quantity, its value for climate studies would be enhanced significantly if CF at the surface is available in addition to $CF(\text{TOA})$. Once $CF(\text{TOA})$ and CF at the surface [$CF(S)$] are available, then CF for the atmosphere [i.e., $CF(A)$] is obtained from:

$$CF(A) = CF(\text{TOA}) - CF(S) \quad (5)$$

where $CF(S)$ is defined as (following the convention used in Eq. 4)

$$CF(S) = F_d^s - F^s \quad (6)$$

where the superscript s denotes fluxes at the surface. $CF(\text{TOA})$ can be determined from satellite radiation budget measurements (e.g., ERBE) and $CF(S)$ from SRB data. Once $CF(S)$ and $CF(A)$ are known individually from observations, the role of cloud forcing in the atmospheric general circulation can be determined. Furthermore, the data would be vital for validating general circulation model simulations of cloud-radiative interactions.

In order to illustrate the nature of the cloud-radiative forcing, the regional distributions of $CF(\text{TOA})$, $CF(S)$, and $CF(A)$ as obtained from a GCM (for a January simulation) are shown respectively in Figures 13, 14, and 15. The following key features of the cloud forcing can be inferred from the results in Figures 13, 14, and 15.

(1) At TOA, the solar forcing and the longwave forcing are of opposite sign. For January, peak values of longwave forcing are manifested over the monsoon region surrounding Indonesia.

(2) At the surface (Fig. 14), the solar forcing is roughly the same magnitude as it is at TOA, whereas the longwave forcing in the tropics is substantially smaller at the surface than it is at TOA. Hence, as shown in Figure 15, much of the longwave forcing due to clouds is felt in the troposphere.

(3) As seen in Figure 15, the longwave forcing due to clouds introduces a significant east-west and north-south asymmetry in tropospheric radiative forcing, particularly in the monsoon region with deep clouds (see the region surrounding Indonesia). The cloud longwave heating can induce rising motions accompanied by sinking in the surrounding clear-sky regions and the resulting overturning can provide the moisture convergence into the monsoon region.

In summary, GCM studies reveal that cloud-radiative forcing introduces significant asymmetries in tropospheric radiative forcing and in the radiative heat flux into the oceans. A carefully orchestrated observational program that combines TOA radiation budget with SRB data can provide vital information concerning cloud-radiative interactions.

3.2 Ocean Heat Budget Studies

The general circulation of the ocean is determined by the following three processes (e.g., see Bretherton, 1984): stress exerted by the atmospheric winds; net heat flux (sum of radiation, latent, and sensible heat flux) into the ocean surface and its meridional gradient; and the balance of fresh

(a) Longwave

(b) Solar

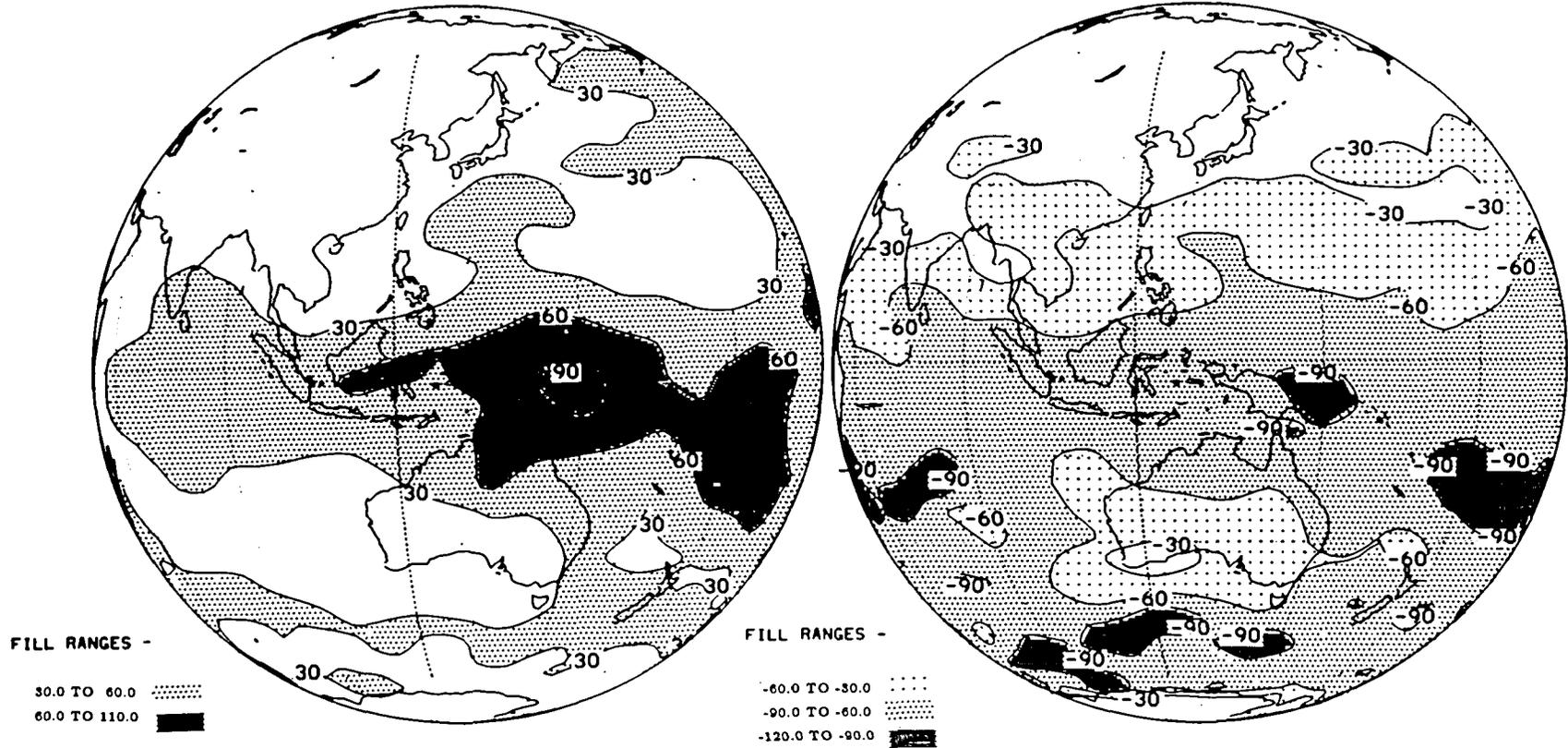


Figure 13. Computed cloud-radiative TOA. The GCM is the same as that described in Figure 3. A 90-day average of the model results is used.

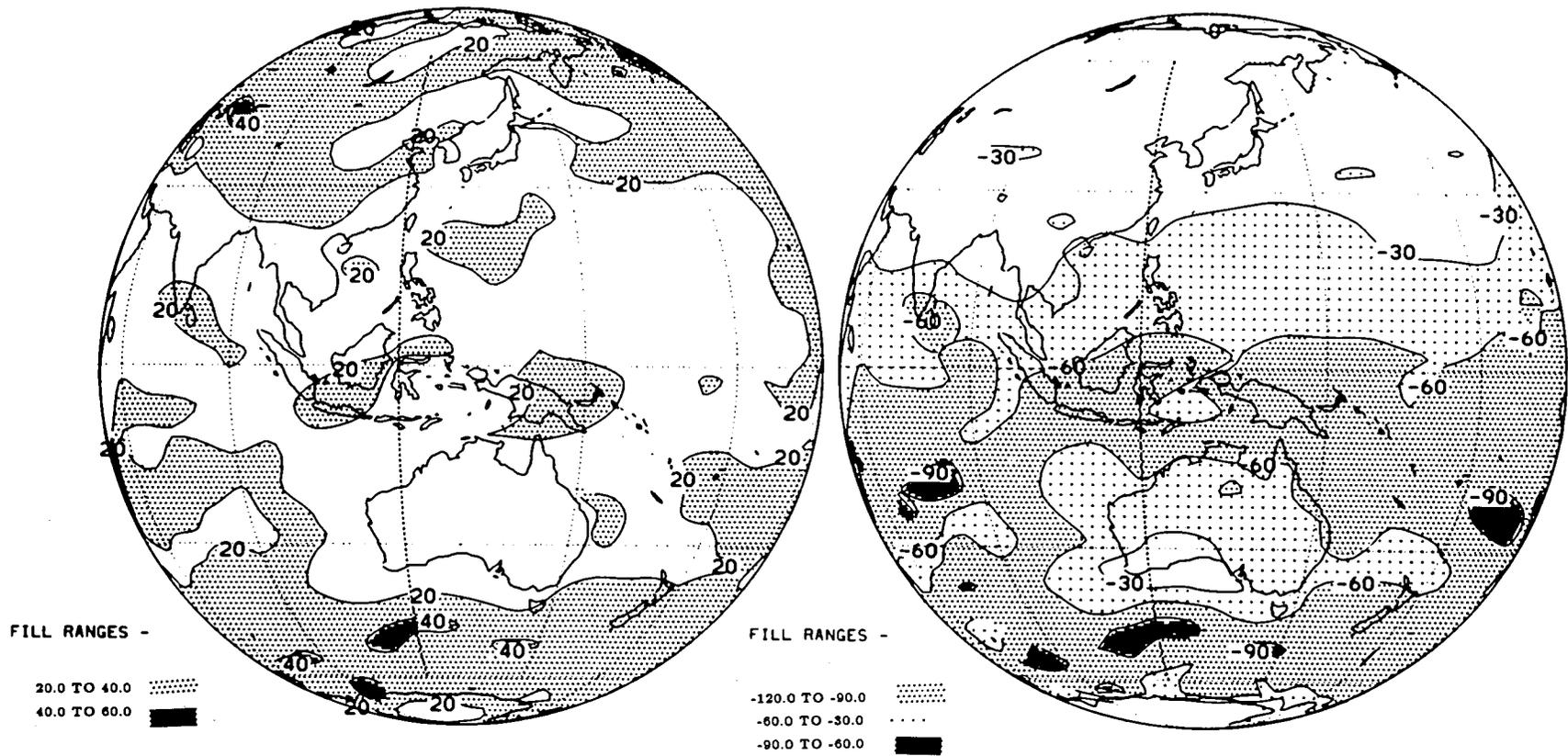
(a) Longwave(b) Solar

Figure 14. Same as Figure 13 but for cloud-radiative forcing at the surface.

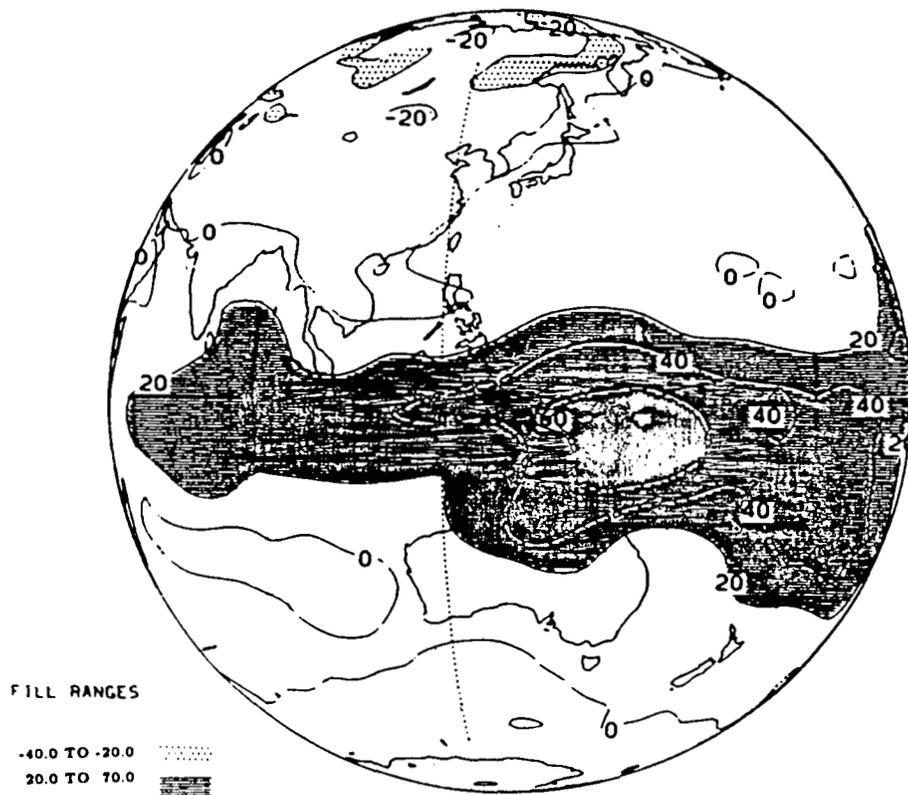


Figure 15. Same as Figure 14 but for cloud-radiative forcing of the troposphere. The solar forcing is not shown since it is generally less than 10 Wm^{-2} .

water, i.e., net of evaporation and precipitation. These three processes together give rise to a myriad of interactions between the ocean and the atmosphere. For example, let us consider the tropics: the trade and monsoon wind systems provide the momentum and vorticity source for the ocean circulation (e.g., see Niiler, 1984); the latent heat flux from the ocean surface is an important thermodynamic energy source for the monsoon wind systems; but the clouds that result from the interaction between the latent heat flux and the monsoon wind systems modulate strongly the solar and longwave energy input to the ocean surface (e.g., see Fig. 14). Such interactions are not restricted to the tropics. For example, in the polar oceans, the formation of sea ice insulates the ocean from ventilating heat to the atmosphere. But the highly reflective sea ice causes a substantial reduction of solar energy deposited in the oceans. The diverse nature of the processes and their time scales require a comprehensive measurement strategy to determine the heat fluxes at the surface. Such surface heat flux data, in addition to providing insights into the processes that govern ocean-circulation and ocean-atmosphere interactions, are also needed to validate ocean models and coupled ocean-atmosphere models.

For illustrative purposes, let us consider one example of model validation. A widely used class of coupled ocean-atmosphere models adopts a mixed layer ocean model (with prescribed mixed layer depth of 50 to 100 m) coupled to an atmospheric general circulation model (e.g., Manabe and Stouffer, 1980). In spite of the fact that such models ignore lateral and vertical heat transport in the oceans, the longitudinally averaged sea-surface temperatures (SSTs) computed by the mixed layer ocean model agree with the observed values to within 2 K (see Fig. 16 adopted from Meehl and Washington, 1985) from 40°N to 40°S. Since SSTs in mixed layer models are determined solely by heat fluxes into the ocean surface, model results such as those shown in Figure 16 suggest that surface heat fluxes are as important as wind stress and fresh water balance in governing the ocean thermal structure. Hence, coupled ocean-atmosphere model studies are forced to compare the computed heat fluxes with observed heat fluxes, even when the quality of the observed fluxes is poorly known. For example, models compare the surface radiative fluxes with “observed” radiative fluxes obtained from outdated empirical expressions (see Fig. 17).

In summary, there is an urgent need to improve the quality of the surface radiation budget data for model studies.

3.3 Long-Term Climate Trends

I will argue here that long-term (decades or longer) measurements of *downward* longwave flux and absorbed solar radiation at the surface can provide fundamentally important information concerning climate feedbacks and their role in governing the climate response to the greenhouse effect due to increases in trace gases (including CO₂).

Let us first consider the longwave flux at the surface. For a doubling of CO₂, the downward emission (by CO₂) increases by about 1 Wm⁻². However, in a radiative-convective model, the surface-troposphere warming of 2 K leads to an additional increase of about 14 Wm⁻² (Ramanathan, 1981). This significant enhancement in the downward emission is due to increases in H₂O and temperature. In a GCM, doubling of CO₂ causes a warming of about 4 K (Hansen et al., 1984; and Washington and Meehl, 1984) such that the downward emission (due to CO₂ doubling) should have increased by about 25 to 30 Wm⁻². The importance and magnitude of the downward emission has generally not been perceived because climate models, and in particular GCMs, analyze only the net flux (up-down) at the surface. The change in the net flux is significantly smaller than the change in the individual components. For example, Figure 18 shows the change in the net longwave flux at the surface computed by a GCM (Washington and Meehl, 1984) for a doubling of CO₂. Considering the north polar region, the model computes a surface warming of 6 K between 50 and 70°N. The increase in the upward emission for a 6 K warming should be about 25–30 Wm⁻². However, the net flux (see Fig. 18)

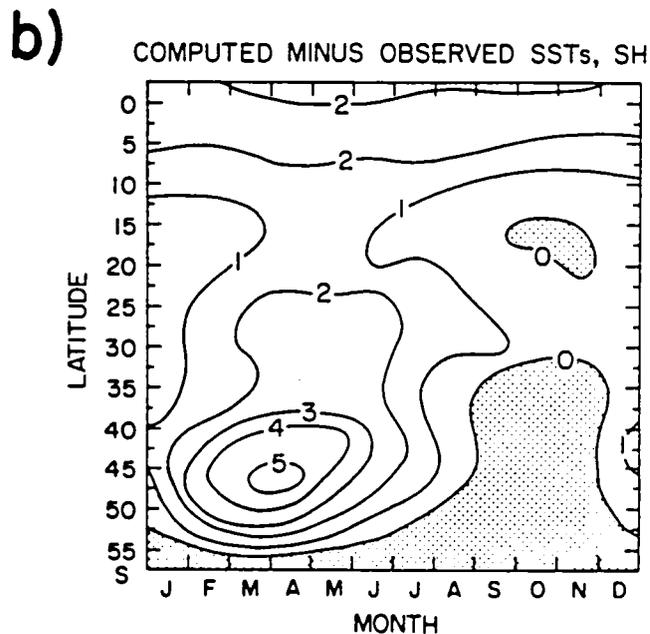
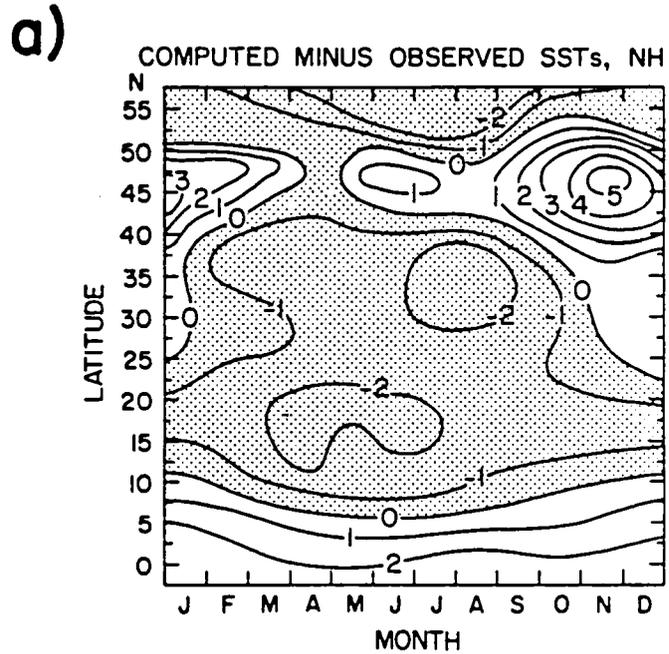
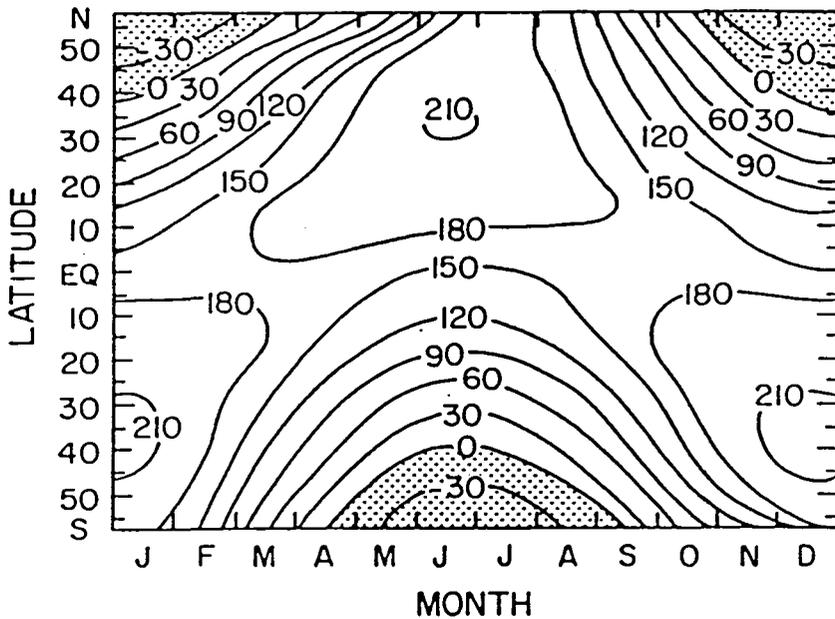


Figure 16. Annual cycle of zonal mean sea-surface temperature (SST) differences (computed minus observed). The model used for the computed values is a mixed-layer ocean model coupled to an atmospheric general circulation model. (a) Northern Hemisphere, (b) Southern Hemisphere. Computed values are 3-year averages. Stippling indicates computed SSTs cooler than observed. (Source: Meehl and Washington, 1985.)

a) COMPUTED NET DOWNWARD RADIATIVE FLUX



b) OBSERVED NET DOWNWARD RADIATIVE FLUX

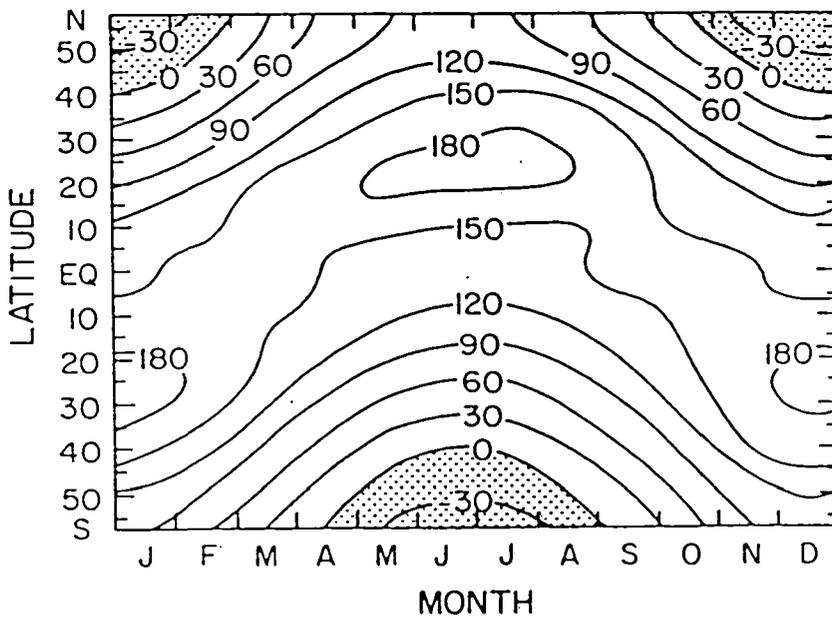


Figure 17. Annual cycle of zonal mean net (down-up) downward radiative flux (sum of solar and net infrared flux at the surface) over ocean only, Wm^{-2} . (a) Computed 3-year average, (b) observed from Esbensen and Kushnir (1981). Positive values indicate downward flux into the ocean. Negative values are stippled. (Source: Meehl and Washington, 1985.)

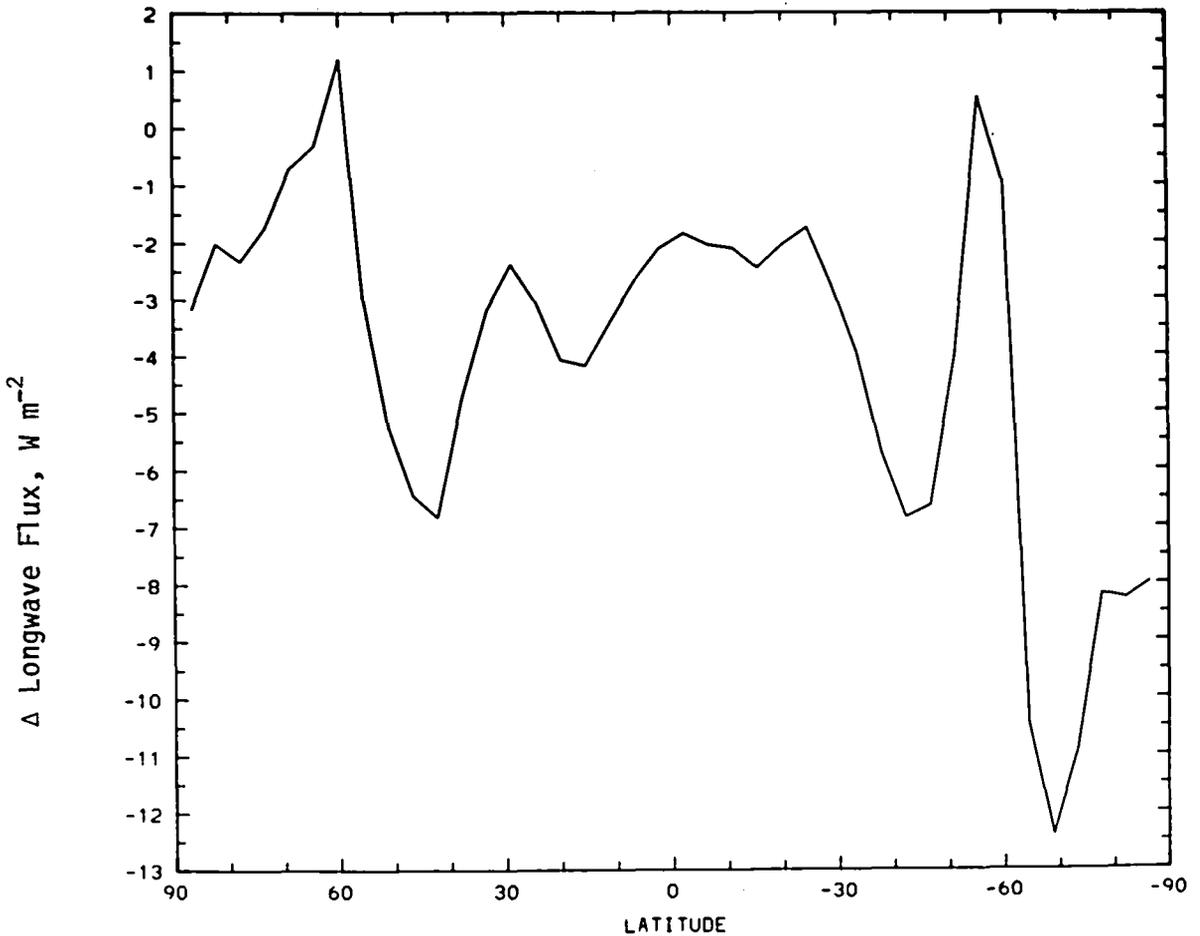


Figure 18. Computed change in the net (up-down) longwave flux (Wm^{-2}) at the surface due to a doubling of CO_2 . For both $1 \times CO_2$ and $2 \times CO_2$, the last 7 years of a 15-year run is averaged to obtain the differences. The results are shown for the December-January-February season. The model is an atmospheric GCM coupled to a mixed-layer ocean model. (Source: Washington and Meehl, 1984.)

decreases by about 2 to 3 Wm^{-2} which implies that the downward flux in the model should also have increased by about 25 to 30 Wm^{-2} . Similarly in the south polar region, where the net flux decreases by about 10 Wm^{-2} , the down flux should have increased by about 40 Wm^{-2} .

It is clear that, if the H_2O feedback is as important as implied by GCMs, the greenhouse warming should be accompanied by substantial changes in downward longwave flux. In addition to changes in longwave flux, models also compute changes in the absorbed solar flux of the order of 25 to 100 Wm^{-2} over the polar oceans (during Spring and Summer) due to CO_2 doubling (e.g., Manabe and Stouffer, 1980; Washington and Meehl, 1984; and Hansen et al., 1984). These changes in the model result from ice-albedo feedback and cloud feedback.

The above GCM results imply that accurate surface longwave and solar flux measurements over a limited number of regional locations (on a long-term basis) would provide vital information about the causes of climate change.

4. SUMMARY

The quality of currently available maps of surface radiation budget data is inadequate for climate studies. Recent approaches which attempt to infer surface fluxes from satellite radiances hold considerable promise for yielding accurate data for solar fluxes. However, most of the current approaches employ narrowband radiances and considerable amount of theoretical and empirical work is required (e.g., along the lines of Davis et al., 1984) to determine the parameters that govern the conversion from narrowband to broadband fluxes. With respect to longwave fluxes, currently there are no promising approaches to infer surface fluxes from satellite information. Model calculations indicate that the top-of-the-atmosphere fluxes are poorly correlated with surface fluxes for clear as well as cloudy skies.

The scientific merits of obtaining SRB data rely crucially on the accuracy of the data. But if the quality of the data in terms of its instrumental and sampling accuracies can be quantified, then, SRB data in conjunction with TOA satellite radiation budget data can improve our understanding of several important problems including cloud-radiation interactions, ocean-atmosphere interactions, long-term climate trends, and land-surface processes.

In this study, I have not attempted to quantify the desired accuracies for SRB data. Such definition of accuracies must await comprehensive empirical studies (based on satellite data) and model simulation studies aimed at characterizing the statistics of variations in SRB on time scales varying from diurnal to seasonal scales and on spatial scales varying from cloud scales to planetary scales. We also need studies that will formalize the procedure of relating the nearly point-source pyranometer measurements to spatially averaged radiances sensed by satellites. It is recommended that such studies be performed first before attempting to orchestrate an observational program for SRB data.

5. ACKNOWLEDGMENTS

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**SURFACE RADIATION BUDGET
OBSERVATIONS AND ANALYSIS**

Thomas H. Vonder Haar

**Colorado State University
and
The Research Institute of Colorado
Fort Collins, Colorado**

Position Paper for

**Panel 2
Workshop on Surface Radiation Budget
for Climate Applications
Columbia Inn, Columbia, MD
17-21 June 1985**

1. HISTORICAL BACKGROUND

The first attempts to estimate radiation budget parameters *within* the earth-atmosphere system by using satellite data were addressed not to the surface budget parameters but to atmospheric absorption parameters. In the early 1960s the study of the generation of available potential energy by diabatic radiative processes was advanced by the work of Suomi and Shen (1963), Smith (1964), Fritz et al. (1964), and Vonder Haar and Hanson (1969). These authors used early TIROS data to estimate absorption of solar energy in the atmosphere, profiles of infrared cooling, or both. Surface measurements of solar energy and/or balloon-borne radiometers were often used as checks on the satellite-based estimates; to build relationships; or together as a data set to study the atmospheric terms.

Of course, empirical methods to estimate insolation, surface net radiation budget, and surface albedo date back many tens of years. They were based upon the sparse surface radiation data measured at the surface. Results of these estimates filled climatological atlases, but unfortunately the uncertainty of these values was large. Thus it was not surprising that Hanson (1971) and others (e.g., Vonder Haar, 1973; Vonder Haar and Ellis, 1975; Tarpley et al., 1978; Ellis and Vonder Haar, 1976, 1978; Vonder Haar and Ellis, 1978) began to use the steadily improving satellite data (ATS, SMS, NOAA) to develop separate empirical and physical techniques to estimate surface radiation budget parameters. Simply filling in the gaps between our limited worldwide surface network of land stations would be good progress; returning information about the surface budget of the oceans would be valued additional information.

Users abounded in the early 1970s as the wave of interest in solar energy was gathering. The matter was discussed in detail at earlier workshops sponsored by NOAA (1971), NOAA/NSF (Turner, 1974), and AES (1978). NOAA/NESS responded with methods and products (e.g., Tarpley, 1979) directed at agricultural and energy users. European scientists also addressed the problem (Raschke and Preuss, 1979; Major, 1976). Gautier and colleagues (e.g., Gautier et al., 1980) tested additional satellite-based methods over eastern Canada and elsewhere while Hay and Hanson (1980), and Smith and Vonder Haar (1980), among others, used the satellite approach for the 1974 GATE with newly available SMS-1 data.

Earlier, implicit filtering techniques such as the minimum albedo method were developed by Raschke and Bandeen (1970) and Vonder Haar et al. (1972) to use NIMBUS satellite data to estimate surface albedo. An early focus on this research sought to separate the snow and ice contribution to the planetary albedo.

As the 1970s ended with the relative demise of solar energy research and the relative rise of climate research we found new interest in the total surface radiation budget and related energy budget parameters. Much of this interest was driven by our continuing and somewhat desperate need for data over ocean regions to address the coupled ocean-atmosphere aspects of climate change. A major study in this regard was the JSC-sponsored CAGE report (Dobson et al., 1982). It recommended no experiment but underscored several research areas needing attention including the estimation of surface radiation budget over the oceans.

In related work Rockwood and Cox (1978) and Norton et al. (1979) had studied the surface albedo over North Africa using satellite data. They were investigating hypotheses of Charney (1975) regarding creeping desertification. Charney's work was stimulated by NIMBUS satellite radiation budget measurements at the top of the atmosphere. Recently, Pinty and Szejwach (1985) used METEOSAT data for similar purposes.

As more observational programs and studies for climate were outlined by NASA, COSPAR, the IAMAP Radiation Commission, and others, we saw the references to surface radiation budget estimates using satellite data increase. The report to JSC (WCP-70, 1983) for the World Climate

Research Program and the recent report by the JSC Working Group on Satellite Global Climate Observing Systems (1985)¹ note some current possibilities for satellite monitoring.

2. DISCUSSION

Can these possibilities become realities to serve climate research? Over land? Over ocean? If not research, are there uses for results and products we can obtain by users in applied climate areas? These user needs are summarized in the position paper from Panel 1 of this Workshop. In the following subsections, we will outline three principal surface net radiation estimation methods available to us. We will also reference published results to demonstrate the methods.

2.1 The Estimation Methods

We recognized three estimation methods:

(1) *The single- or multi-channel satellite radiation approach.* The approach subdivides into two types of methods: physical and statistical. Both are based on the radiative transfer situation shown in Figure 1 for the solar radiation (insolation) part of the problem.

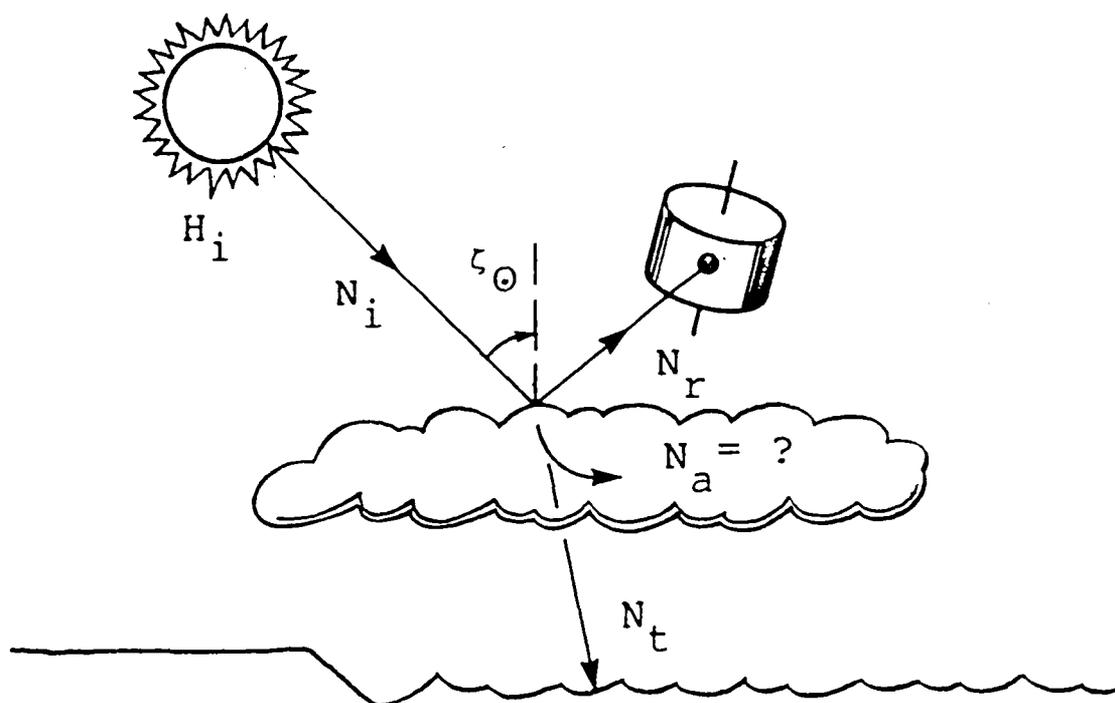


Figure 1. Radiative transfer for solar radiation in a cloudy atmosphere.

¹Informal reports of Working Group, personal communication, Dr. Thomas Kaneshige, JPS, WMO, Geneva.

With a satellite measurement of reflected radiance N_r , we obtain the instantaneous directional reflectance $r = \chi N_r / H_i \cos \xi$ for the earth-atmosphere system viewed by the satellite instrument. (χ = bidirectional reflectance function; ξ = solar zenith angle; and H_i = direct solar irradiance.) Since we wish to determine $H_s N$, the solar irradiance reaching the surface, we note the atmospheric transmittance $t = \pi N_r / H_i \cos \xi$ and use the relation $1.0 = r + t + a$. Under the assumption that the absorptance of solar energy in the atmosphere a can be assumed or determined from separate measurements we may obtain $H_s = N_r$, our estimate of insolation based upon a satellite measurement. The physical methods of this type explicitly estimate H_s .

Statistical methods are developed from sets of satellite measurements (the independent variables) with concurrent pyranometer or net radiometer measurements at the surface (dependent variables). This general approach is more complex for the estimation of the total surface radiation budget and has fewer proponents for this application.

(2) A second approach uses a *radiative transfer model* together with any available input data related to the temperature, moisture, and cloud structure of the overlying atmosphere. Depending upon both the quality of such input data and upon approximations in the model, this approach can estimate the insolation and/or surface radiation budget.

(3) The third approach has been used for many years; it uses *only surface observations* to estimate the desired parameters. It is either based upon site-specific empirical methods or averaged climate data sets.

2.2 Synopsis of Present-Day Results

2.2.1 Estimates of Solar Radiation Reaching the Surface

By far the greater amount of published results apply to the solar energy estimation problem. Figure 2 from Gautier et al. (1980) and Figure 3 from Smith and Vonder Haar (1980) demonstrate the greater success in estimating the insolation at *tropical latitudes*.

Justus and Tarpley (1984) have summarized a large number of estimates using the statistical satellite radiance method of Tarpley (1979). Raphael and Hay (1984) have provided a comparison of three methods (Hay's, Tarpley's, and Gautier's physical methods). Results from their intercomparison are shown in Figure 4. Recently, Möser and Raschke (1984) developed a method using METEOSAT-II data and Raschke² has used the ISCCP B3 data set to estimate solar energy reaching the surface over both Europe and Asia. The later work is discussed elsewhere in this workshop report.

2.2.2 Estimates of Surface Radiation Budget Components and the Total Surface Heat Flux

Significant recent work has been done on the total surface heat flux using the classical surface empirical approach. Figure 5 from Dobson et al. (1982) displays monthly average results from their work over Ocean Weather Station (OWS) Delta in the North Atlantic. They determined the net short-wave radiation (Q_S), the net longwave radiation (Q_L), and the total surface heat flux including the sensible, latent, and radiation heat fluxes.

Lind and Katsaros (1981) developed a simple radiative transfer model approach using surface and upper air data from JASIN (Figure 6). The output from their method is downward infrared radiation at the surface. When checking their method against in situ observations of net radiation from ships they found considerable uncertainty in the method as can be seen in Figure 7. Recently Chou (1985) applied his model method to the tropics and Schmetz et al. (1985)³ are testing a net radiation estimation method over Europe.

²Personal communication.

³Personal communication.

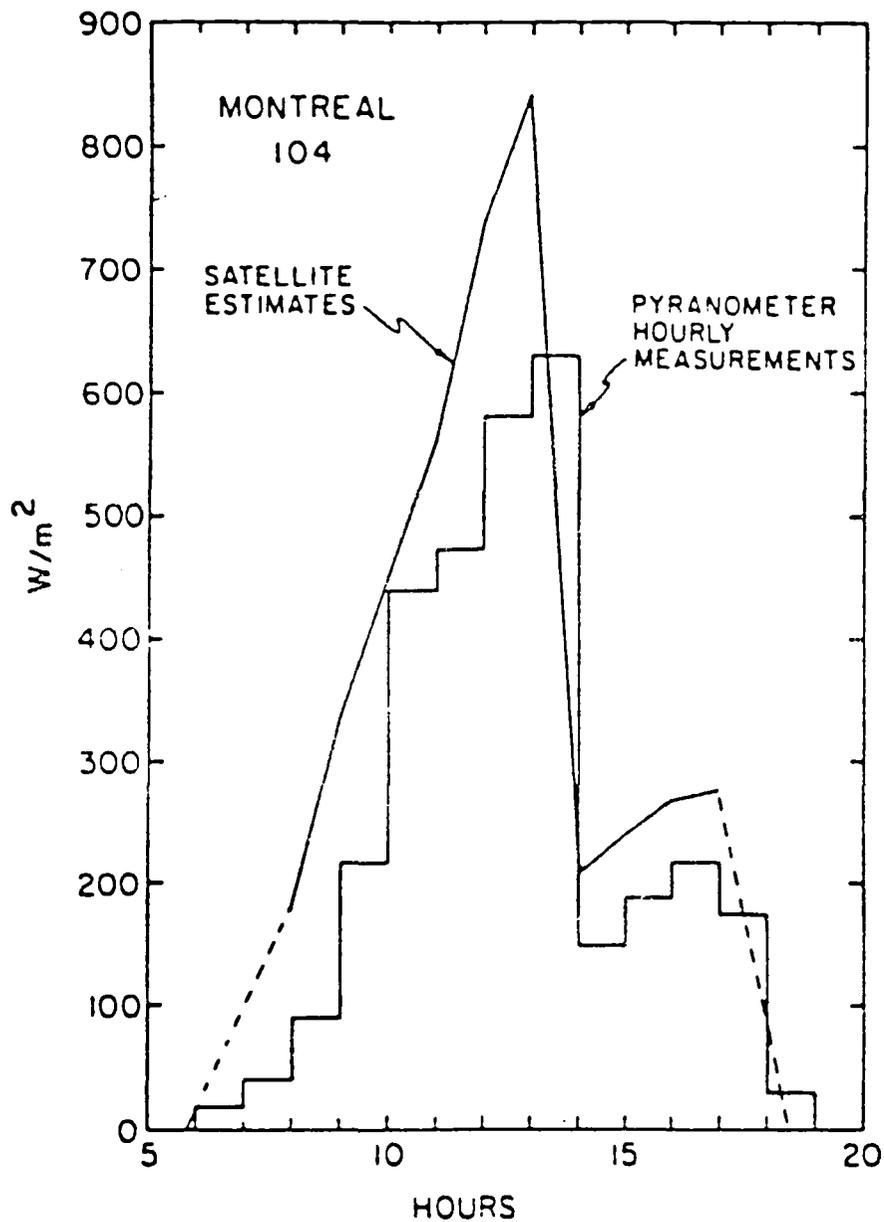


Figure 2. Insolation variation with time for day 104, Montreal. Solid line for clear day and dashed line for partly cloudy day. (From Gautier et al., 1980.)

USING VARIOUS SATELLITE WINDOWS
 PHASE 3: GILLIS DIURNAL AVERAGE

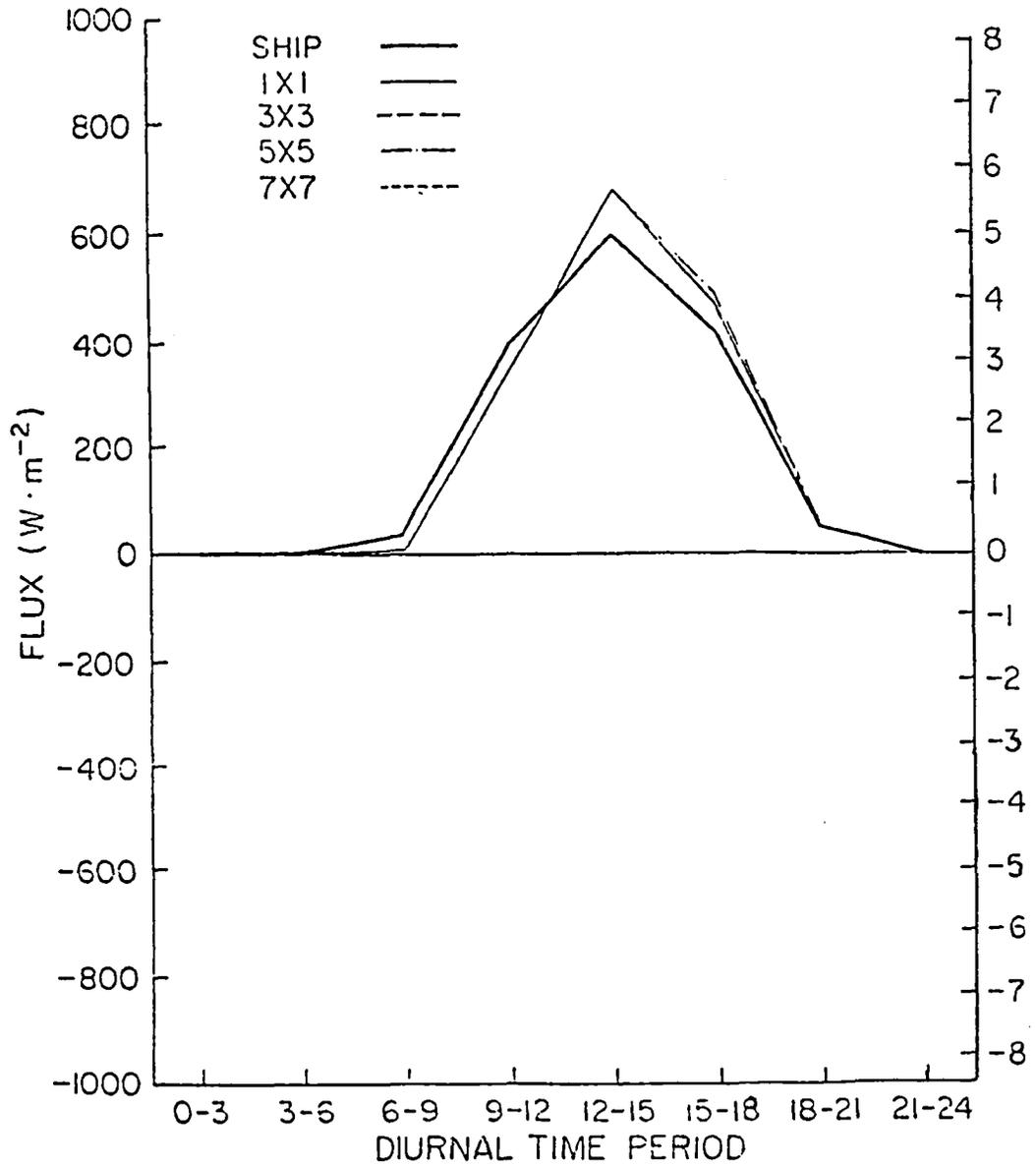


Figure 3. Comparison of $K\downarrow$, from ship and satellite parameterization. (From Smith and Vonder Haar, 1980.)

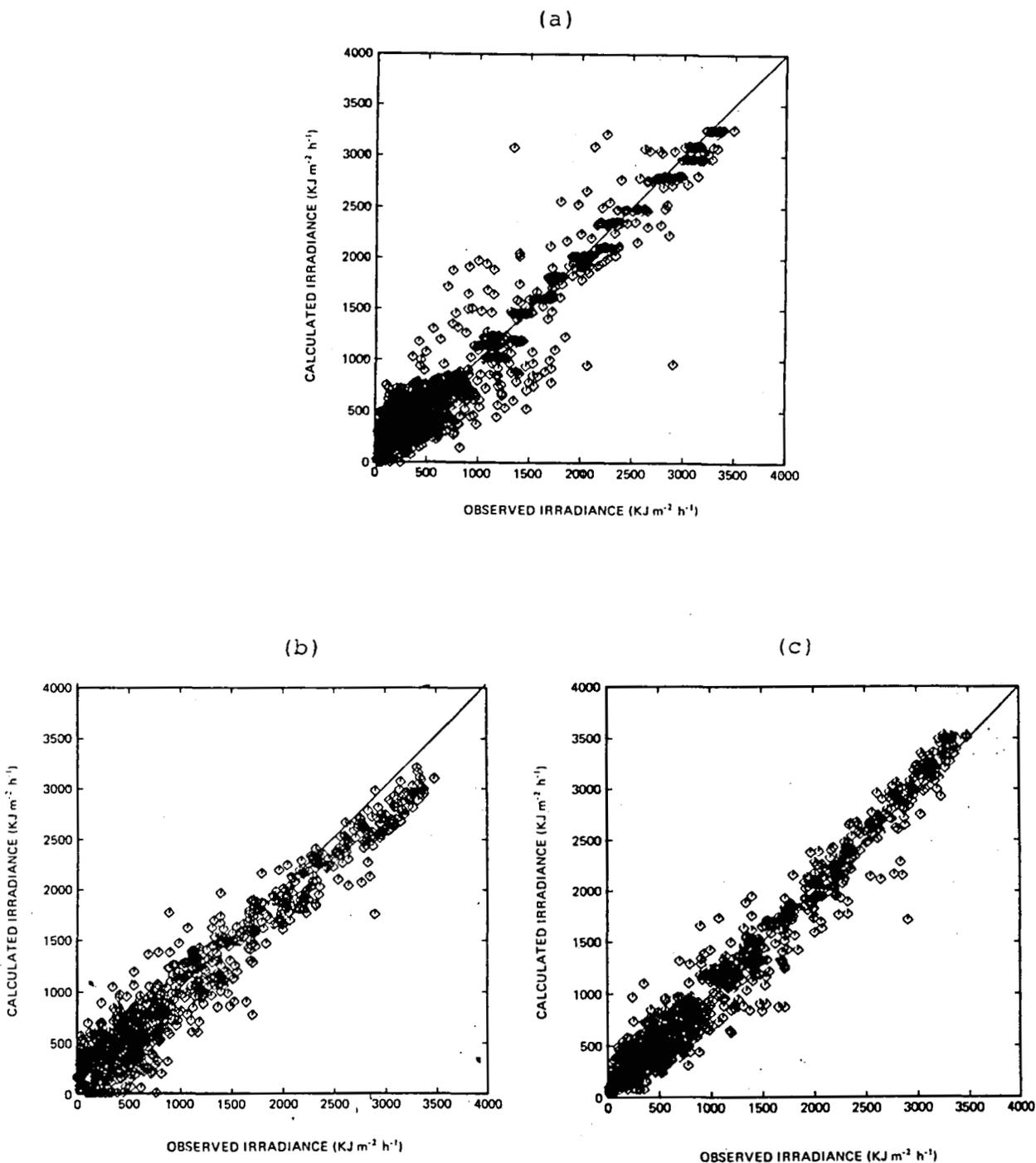


Figure 4. Hourly values of measured and estimated radiation at the 12 stations for the nine-day sample using methods of Tarpley (a), Hay (b), and Gautier (c). (From Raphael and Hay, 1984; J.C.A.M. © American Meteorological Society.)

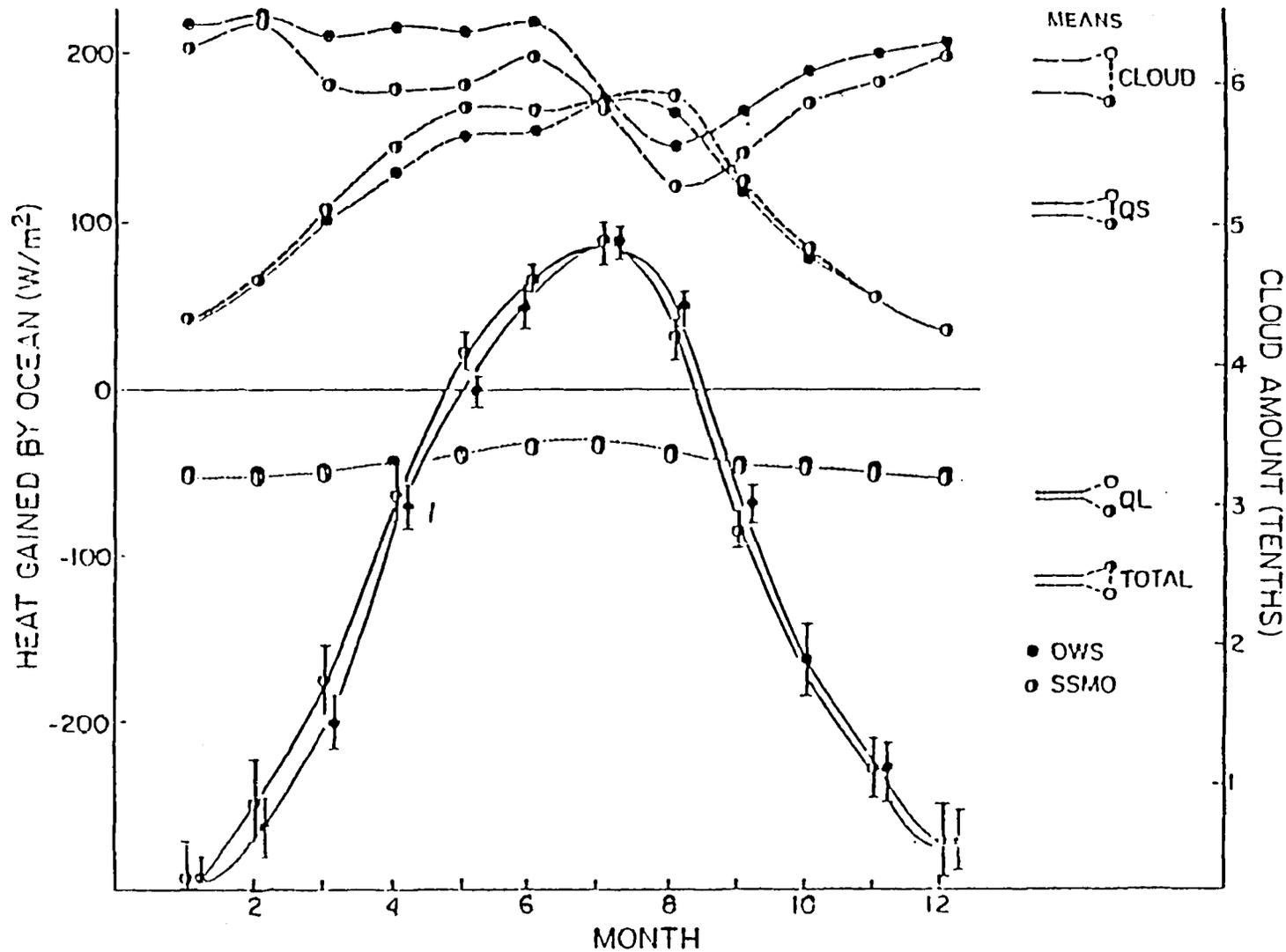


Figure 5. Annual cycle of net surface radiation components (shortwave, Q_S , and longwave, Q_L), cloud cover, and total surface heat flux (including sensible, latent, and radiation fluxes) based on a 20-year data record at Ocean Weather Station (OWS) Delta, 42°N. Comparisons to results from bulk formulae calculations with Surface Ship Meteorological Observations (SSMOs) are shown. (From Dobson et al., 1982.)

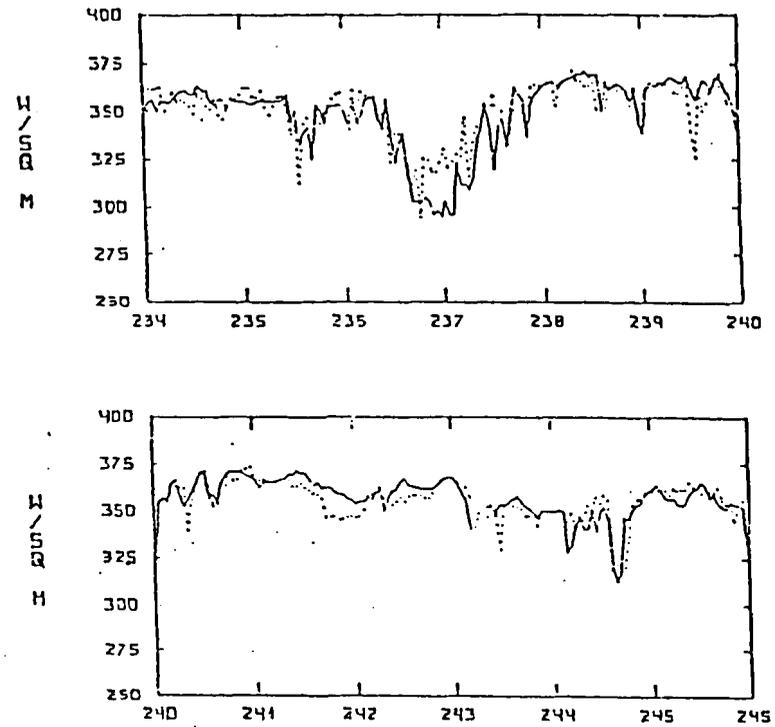
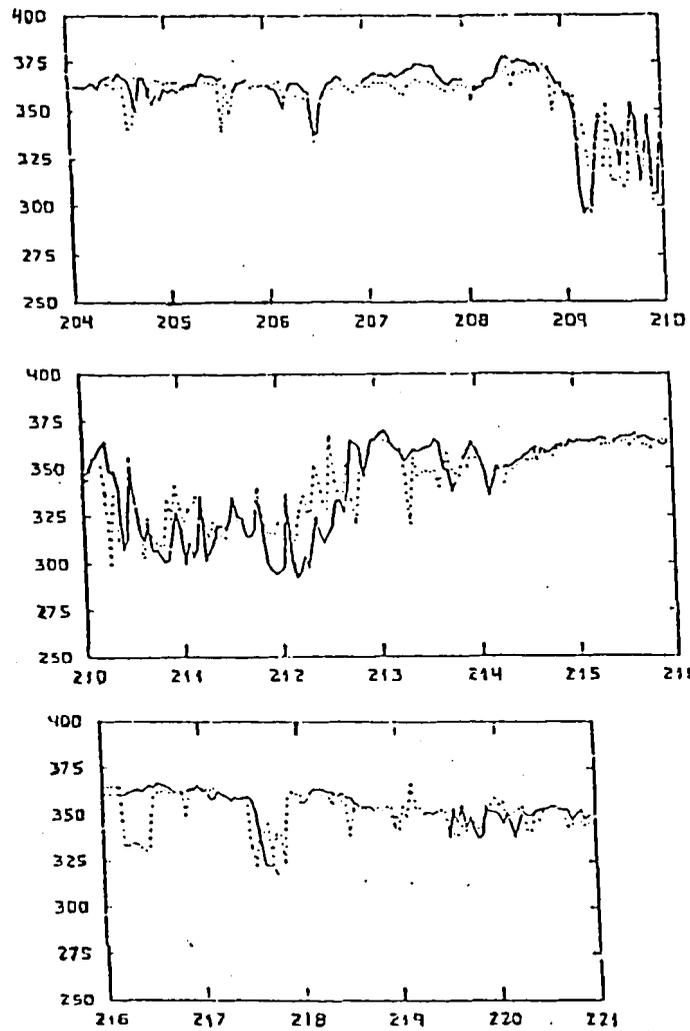


Figure 6. Hourly values of model estimates and measurements of atmospheric longwave flux in Wm^{-2} . (From Lind and Katsaros, 1981.) Data is from 59°N, 12°30'W. Estimates are shown as the dotted line and measurements are shown as the solid line.

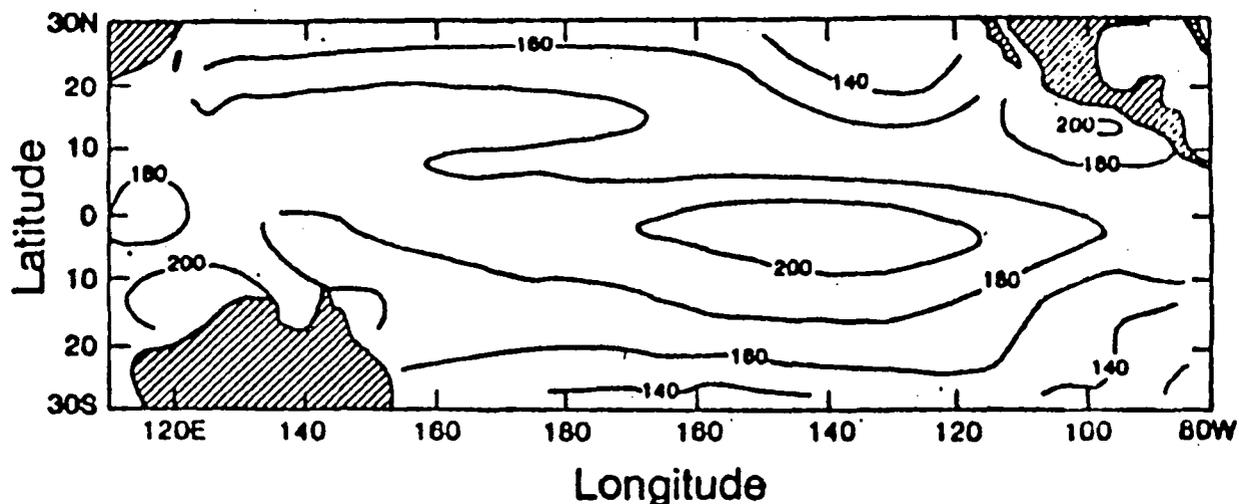


Figure 7. Annually averaged net gain of radiative energy (Wm^{-2}) in the tropical Pacific Ocean for the period 1970-78.

2.3 The Present Workshop

I will not pre-empt the work and discussions of the observations and analysis panel in this workshop by reviewing all current methods to estimate surface radiation budget terms using satellite data and other methods. Their pros and cons, their appropriate time and space scales, the physical or statistical basis for the techniques, results to date, and estimated accuracy will be summarized after the work of this meeting is completed.

It suffices to note from section 2.2 that not only have a sufficient body of methods and techniques been proposed since the early 1970s but that many have been demonstrated. Some have even been checked or tested with independent measurements. It is especially timely to review the methods now because:

- (1) the second phase of observational projects for the World Climate Research Programme is being formed,
- (2) new (some radically new) satellite observation systems will soon become realities (e.g., lidar, passive microwave measurements from geosynchronous altitude, space platforms with companion satellites), and
- (3) scientific results related to our study of surface energy budgets continue to be developed (e.g., Otterman et al., 1984; Meerkötter and Grassl, 1984; Dugas and Heuer, 1985; Pinker and Corio, 1984; Pinty and Szejwach, 1985).

3. KEY QUESTIONS AND TASKS

3.1 Natural Separation of the Problem

It has been apparent since the 1984 GATE experiment that the estimation of the total surface radiation budget naturally divides itself into separate problems of (a) the "tropics" (e.g., all regions having a water vapor overburden of >3 cm) and (b) the rest of the world. The "super greenhouse" effect observed during GATE for the tropics causes the net *infrared* budget at the surface to be virtually unchanged ($\pm 10 Wm^{-2}$) regardless of overlying cloud conditions (Figure 8b). Thus, estimation

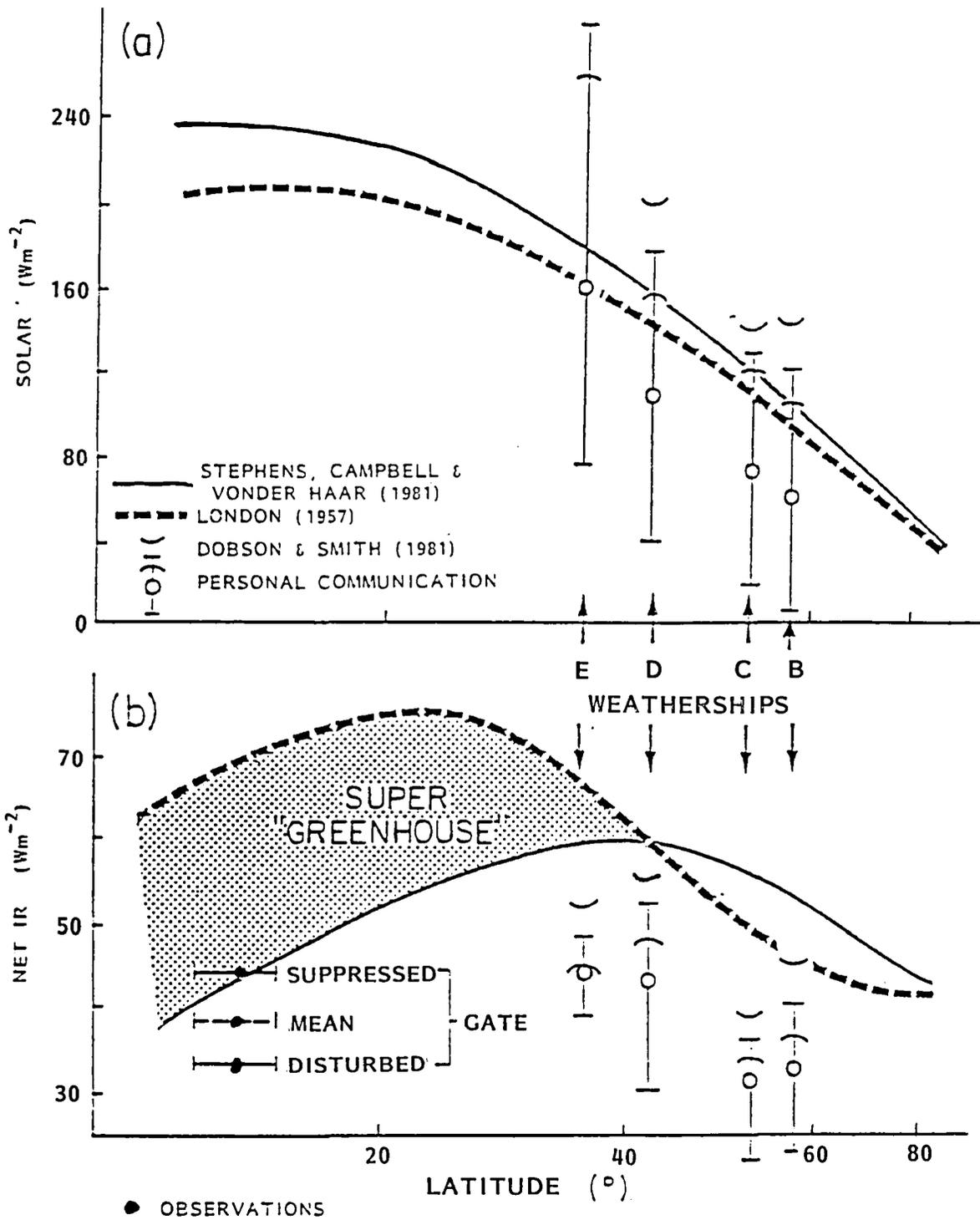


Figure 8. Mean zonal profiles. (a) Solar radiation reaching the surface. (b) Surface net infrared radiation.

of the insolation and surface albedo (quite easy over oceans) allows estimation of the magnitude and variation of the total surface radiation budget. Clouds primarily (and other aerosols secondarily) provide the “shutters” to control the net radiation gain at the surface.

3.2 The Most Challenging Task

Outside the tropics, as defined above, we face a much more complex problem. Both the downward infrared irradiance and the solar energy reaching the surface are greatly influenced by overlying clouds and by variations in atmospheric water vapor and thermal structure (for the infrared). Lind and Katsaros (1981), Meerkötter and Grassl (1984), and others have begun to attack the infrared problem. This will be our single-most-challenging task in the surface radiation budget research area.

3.3 Angular Reflectance Problems

The nontropical region contains a great deal of land mass in the northern hemisphere. Surface albedo varies with vegetation, snowcover, and angle of illumination. The bidirectional problem of (often low angles of) solar illumination coupled with cloud reflectance properties makes the estimation of solar budget terms more difficult than at lower latitudes. We will obtain some assistance here from techniques (e.g., ISCCP) devoted to detection of clouds “per se.”

3.4 Need for Improvements in Theory

Radiative transfer theory will provide vital support to the design of satellite-based estimated method (e.g., Stephens et al., 1981). Theory will also aid us as we check results, especially since good, routine pyrogeometer data are practically nonexistent. However, on the solar side our SRB efforts must confront the “solar absorption paradox” identified more than 10 years ago (e.g., Reynolds et al., 1978) and still currently a matter of active discussion in the field (Twomey, 1976; Welch et al., 1980; Wiscombe et al., 1984; Fouquart, 1985). If we cannot reconcile the difference between in situ observations of solar energy absorbed in clouds with calculations of the same, our SRB estimation methods (and tests) will be laced with that uncertainty.

4. A LOOK TO THE FUTURE

Overall, I am optimistic about our possibilities to obtain very useful climate data from satellite-based estimates of surface radiation budget. However, we may not meet all needs in all regions of the world. One reason for optimism is the strong and continuing body of effort placed on the problem by scientists today. We have a critical mass of talent.

Secondly—and equally exciting—I see a new generation of satellite observational possibilities. Obviously, we will be aided by more selective spectral radiation measurements of higher radiometric precision. Soon we will have new time domain (geosynchronous) microwave capability. Mid-latitude moisture, temperature, and liquid water measurements using passive microwave detectors on GOES-NEXT class spacecraft will be possible in the early 1990s. Lidars from low earth orbiters offer special support to our problem. Shuttle- or platform-based instruments will aid intercalibration of the data we use and they also offer a platform to test many new sensors.

While climate modelers struggle with the problems of coupling the oceans and of explicit cloudiness, I believe the climate observational program from space will make additional advances beyond the excellent starts on planetary radiation budget and cloud measurements. The surface radiation budget area may well be one of the accomplishments of the early 1990s.

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**SURFACE RADIATION BUDGET
CALIBRATION AND VALIDATION ACTIVITIES**

H. Grassl

GKSS-Forschungszentrum
Max-Planck-Strasse
D-2054 Geesthacht, FRG

Position Paper for

Panel 3
Workshop on Surface Radiation Budget
for Climate Applications
Columbia Inn, Columbia, MD
17-21 June 1985

1. INTRODUCTION

The differential solar heating of the planet Earth is the driving force of general circulation in the atmosphere and ocean. The only conceivable way to obtain a global view of energy budget terms (such as the radiation budget components at the top of the atmosphere or at its surface, the latent or sensible heat fluxes at the atmosphere's surface, and the meridional transports both in the atmosphere and in the oceans) is via observations from space. While the energy budget is simply a radiation budget at the top of the atmosphere and is now accessible to satellite measurements, the radiation budget at the surface is only one of three components of similar magnitude which often changes sign daily. Therefore, the discussion of the radiation budget at the surface as related to climate applications should not be isolated but discussed together with latent and sensible heat flux (see Table 1). Up to now the surface energy budget has been mainly inaccessible to remote sensing from space. Although the surface radiation budget (SRB) is of vital interest to mankind, knowledge of its effects over most parts of the globe has been poor. Moreover, since ocean/air interaction is the central mechanism for climate time scales that are important for society and is therefore the central research topic within the World Climate Research Program (WCRP), information concerning the SRB over the oceans also becomes urgently needed. One central question of the workshop discussions therefore should be: Is the best way to measure SRB over the oceans directly from satellites or from quantities that can be measured in an easier manner, either by in situ or by remote measurements?

TABLE 1. Range of Surface Energy Budget Terms (Downward Positive) and Conditions Leading to Maxima and Minima

Net Radiation R	
Bandwidth:	$-200 \text{ Wm}^{-2} < R < + 1000 \text{ Wm}^{-2}$
Minimum:	warm desert surface at sunset (R is simply the longwave net flux)
Maximum:	zenith Sun in a clear atmosphere onto a cool and dark (water) surface
<hr/>	
Sensible Heat Flux H	
Bandwidth:	$\sim \text{some hundred } \text{Wm}^{-2} < H < \sim + 100 \text{ Wm}^{-2}$
Minimum:	cold air outbreak from polar ice or a snow-covered continent to a rather warm ocean
Maximum:	heating of a desert near noon warm air flowing from a warm continent onto a cool water surface
<hr/>	
Latent Heat Flux L	
Bandwidth:	$\sim -1000 \text{ Wm}^{-2} < L < \text{few } \text{Wm}^{-2}$
Minimum:	strong winds blowing very dry air onto a water surface or a swamp
Maximum:	dew forming at the surface

The main objectives of the workshop are discussed in sections 2 to 4, and calibration and validation activities (present and planned) are discussed in sections 5 and 6.

2. CURRENT STATE OF KNOWLEDGE

2.1 Conventional Measurements

Measurements of SRB components date back to the last century and seem rather easy at first glance. However, there are only a few locations on continents where all four components (downward and upward fluxes of shortwave and longwave radiation) are measured continuously. The number of

stations with well-calibrated instruments is small and often large areas of a continent have no single station. The absolute accuracy of shortwave radiation flux measurements still does not reach two percent for the most carefully run stations and increases to more than five percent for all those stations without a radiation expert. Most stations are not equipped with radiometers that measure longwave fluxes since most radiometers only allow longwave plus shortwave incoming flux measurements that during daytime render the separation of the longwave flux ($\sim 300 \text{ Wm}^{-2}$) from the shortwave flux (up to $\sim 1000 \text{ Wm}^{-2}$) difficult. The knowledge of longwave net flux behavior with clouds, water vapor content, and surface heating or cooling at the surface is inferior to the knowledge of shortwave flux variations with cloud parameters and atmospheric turbidity, although longwave net flux variations (reaching only -200 Wm^{-2} under extreme conditions) are rather small (see also Table 1).

2.2 Parameterizations

When SRB is derived via parameterization with other surface or atmospheric parameters, we should also look for other surface energy budget terms that under certain conditions, such as stormy weather over an ocean, may surmount SRB values considerably.

We need careful modeling studies on optimum wavelength positions and the number of channels for: (1) SRB at a given accuracy, (2) SRB from future operational meteorological satellites, and (3) SRB verification by application to already existing data.

There are numerous formulas that try to parameterize both the shortwave and the longwave SRB in terms of standard meteorological variables and thus calculate SRB for areas without direct measurements. Accuracy is first of all a function of the number of details in cloud observation since amount, type, and optical depth of clouds mainly determine shortwave atmospheric transmission and sky emission. Applying different parameterizations derived from coastal stations or weather ships for SRB over oceans may shift the isoline of a balanced energy budget by 10° in latitude, when other heat fluxes are fixed.

2.3 SRB From Satellite Data

Recent attempts to derive the shortwave SRB over continents from satellite measurements have shown very promising results (Diak and Gautier, 1983; Möser and Raschke, 1984; and Stum, 1984), as long as only weekly or monthly averages are sought. The extension to ocean areas and shorter time averages faces the central problem of nearly all recent remote sensing methods: the lack of accurate in situ truth data.

The first steps toward the estimation of longwave SRB from spectral radiances at the satellite height have also been taken (Smith and Woolf, 1983; and Meerkötter and Grassl, 1984), but their reliability still has to be proven.

Sea surface temperature (SST) is the parameter occurring in all energy budget terms except incoming solar radiation. If the SST rms error is below 1 K, which is true not only for ocean weather-ship and buoy data but also for the split window technique of the NOAA 7 satellite, then longwave emission of the ocean surface is more accurate if it is calculated rather than measured.

3. REQUIREMENTS FOR CLIMATE STUDIES

The complex interactions within the climate system components (atmosphere, land, ocean, cryosphere, and biosphere) and among these components are ultimately driven by the unbalanced radiation budget at the top of the atmosphere. Information on other levels within the atmosphere

and at the ground, in addition to the budget values at the top of the atmosphere, is also needed to complete climate studies. However, radiation parameters cannot be the only criteria used. SRB is part of the surface energy budget and should not be discussed as an isolated entity.

The accuracy needed for all energy budget terms increases according to the particular region covered by climate studies. For instance, the accuracy level for the North Atlantic energy budget has to be known within $\pm 10 \text{ Wm}^{-2}$ accuracy; however, the accuracy level reached for global studies of the interannual variability of the budget at the top of the atmosphere has to be $\pm 1 \text{ Wm}^{-2}$. Since complete coverage of the area studied is necessary for all climate studies, satellite measurements are a prerequisite of climate studies. These satellite measurements have to be supported by careful in situ truth data at some anchoring stations. Local measurements have to be integrated very carefully to the size of a satellite radiometer pixel over inhomogeneous terrain or under broken cloud conditions. Since the surface energy budget is needed, SRB determination should favor net flux estimates rather than those for upward or downward fluxes separately. However, if one flux component (for instance, surface emission) is accessible by accurate measurements of another parameter (this parameter has to play a major role in the parameterization adopted) then the other flux component has to be estimated separately.

4. PRIORITY DIRECTIONS FOR FUTURE SRB RESEARCH

4.1 Satellite Measurements

Clouds interfere strongly with the entire spectral band from the $0.3 \mu\text{m}$ to $100 \mu\text{m}$ wavelengths, where most of the radiation flux from the Sun and from terrestrial radiation is contained. Also, many atmospheric gases strongly absorb shortwave and longwave radiation leaving only two major windows from the $0.3 \mu\text{m}$ to $0.7 \mu\text{m}$ and $9 \mu\text{m}$ to $13 \mu\text{m}$ wavelengths. Hence, we cannot have an unobscured view of the Earth's surface from a satellite under all weather conditions within this radiation energy containing a spectral band. SRB estimates from broadband channels in cloudy areas have to be inaccurate and will not meet accuracy requirements of climate studies.

Besides broadband radiances we also have to measure radiances in different opaque bands or in transparent spectral bands, namely the microwave region, in order to vary or reduce the optical depth of clouds so strongly that surface characteristics can be inferred or seen. However, we are then forced to have parameterizations of energy budget terms with quantities that are much more easily measured. In other words, measurements in broad channels, sufficient for the top of the atmosphere radiation budget, have to be augmented by narrow spectral channels in windows and wings of absorption bands to be able to distinguish between different targets (cloud or surface type, cloud amount, and cloud optical depth) and to derive important parameters for a radiation flux parameterization.

4.2 Surface Measurement

The main need for surface measurements of radiation fluxes in SRB for climate applications is their use for calibrating and validating satellite measurements. The density of the surface network on continents should not be increased; however, a few stations should be run carefully and then used for the integration over a satellite radiometer pixel or a number of pixels. This procedure should be repeated under different conditions, i.e., these stations should be anchoring or calibration stations for the International Satellite Land-Surface Climatology Project (ISLSCP). Other carefully run stations should then be used for a validation of the calibrated satellite radiometers.

More reliable data over the oceans from research vessels are urgently needed. Up to now, practically no data exist except historical data from former weather-ship stations and from a few cruises especially during the GARP Atlantic Tropical Experiment (GATE).

5. CALIBRATION

Calibration is defined as the absolute calibration of a radiation sensor. Since the measurement of SRB for climate applications needs complete coverage and therefore satellite data, the calibration of radiometers has to be included in this section. While it is obligatory for most ground stations to calibrate solarimeters and pyrgeometers in regular intervals, many satellite sensors have no onboard calibration, even though this measurement would give calibrated radiances globally from only one sensor.

5.1 Satellite Radiometer Calibration

The main drawback for the acceptance of satellite data, for instance, in meteorological services, is very often inadequate calibration. This either forces users into time-consuming and costly calibration procedures (for example by airplane underflights) or leaves the data untouched. Onboard calibration is the easiest for narrow thermal infrared channels since the temperature of the calibration blackbody is controlled more reliably than the spectral behavior of a degrading diffuser plate for the shortwave spectrum. The group should discuss recently proposed calibration procedures for satellite radiometers for the longwave and shortwave spectral band (Kriebel and Reynolds, 1984; and Lorenz, 1984).

5.2 Ground-Based Radiometers

The group should encourage WMO and other international organizations to pursue and strengthen the calibration work already done and should point to the need for an increased number of stations measuring longwave downward flux, especially on weather ships or small islands.

6. VALIDATION

This section defines the term validation (for satellite data only), derives possible consequences for SRB estimation, and gives a few recommendations.

6.1 Definition

The word validation is present in all reports on satellite data: however, it is used in many different aspects. The following attempt at a broad definition should be discussed at the workshop.

Validation = determination of reliability, consistency and/or accuracy of data by:

- (1) plausibility test
- (2) simple physical constraints
- (3) forcing to a known or assumed integral value
- (4) comparison to in situ measurements at a few locations and a few dates
- (5) comparison to radiative transfer modeling
- (6) comparison to parameterizations in terms of easily accessible parameters for the quantity sought

Examples for the above-mentioned points are:

- (1) No strong gradients of surface temperature in subtropical oceans
- (2) Brightness temperature below 273 K in an area partly covered by sea ice
- (3) No energy loss or gain within one year at the top of the atmosphere for the entire globe
- (4) Global radiation (surface shortwave flux) derived from Meteosat fixed to the surface network over Central Europe

- (5) Cloud detection and classification at night with NOAA 7 by comparison to modeled brightness temperature differences of the IR channels (Olesen and Grassl, 1985)
- (6) Determination of cloud amount, cloud type, and cloud optical thickness from rather narrow spectral channels (ISCCP) and subsequent application of a proven parameterization for shortwave and longwave downward radiation flux as a function of cloud parameters

6.2 Problems

While up to point (4) validation procedures are rather straightforward and well-accepted now, the wealth of satellite data together with more sophisticated remote sensing methods and the lack of reliable in situ truth data will increase the number of validation attempts by the procedures discussed in points (5) and (6), of section 6.1.

A major problem is inherent in point (4): How can a rare and strictly local measurement of net radiation in a complex terrain be fit to a satellite pixel covering at least a square kilometer? The answer is to add data sets on land use (thus surface emissivity) and surface albedo (as well as momentarily observed cloud parameters) to acquire the correct calculation of pixel sized net radiation and to compare these results to an absolutely calibrated broad channel satellite radiometer. Since only part of the needed information is available, in most cases validation according to points (1) to (3) in section 6.1 also has to be applied.

6.3 Recommendations

(1) Satellite radiometers need narrow spectral channels in the windows and wings of absorption bands in addition to broad channels to account for the absorption and emission characteristics of the atmosphere. These characteristics constitute the link between upwelling radiances at the top of the atmosphere and surface fluxes.

(2) In situ truth data should not be the benchmark for which to judge all satellite data since very often the in situ truth data measure different parameters at a different location and at different times (i.e., surface skin temperature versus bulk sea temperature) and contain errors also.

(3) Validation types 1 to 3 should always be included for the validation of SRF components.

(4) The modeling of radiative transfer should accompany the development of new remote sensing methods, and the combination of validation types 1 to 3 and 5 should be considered adequate if no reliable in situ truth data are available.

(5) Extreme care should be taken to integrate ground truth data over a satellite pixel in order to have really comparable quantities.

7. PROCEDURE FOR ESTIMATING SRB FROM SATELLITES

The following steps, which are ordered according to growing complexity, show how we should proceed when searching SRB from spectral satellite radiances.

(1) Whenever SRB components can be estimated sufficiently and accurately directly from broadband and narrowband radiances at satellite height, no deviations using existing ground-based parameterizations of fluxes should be followed.

(2) If direct estimates of SRB components are not accurate enough, other surface parameters derived in an easier manner from satellite radiances have to be used as input for existing ground-based parameterizations.

(3) If the additional parameters are insufficient for existing ground-based flux parameterizations, then specially adapted parameterizations should be developed.

(4) If approaches (2) and (3) do not promise success, after careful accompanying model studies, the satellite data has to be supported by easily available ground truth data.

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**SURFACE RADIATION BUDGET
DATA SETS DEVELOPMENT**

G.E. Hunt¹

**Centre for Remote Sensing
Imperial College
London, SW7 2BZ**

Position Paper for

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¹ Authored the Position Paper but was unable to attend the Workshop.

1. INTRODUCTION

This position paper has been compiled from contributions provided by G.E. Hunt (U.K.), J. London (U.S.A.), C.G. Justus (U.S.A.), E. Raschke (Germany), W.B. Rossow (U.S.A.), and P. Taylor (U.K.). The paper addresses the topics of the data sets that are currently available, the accessibility of these data to the scientific community, and the requirements to support the current and future activities of experiments associated with climate. Consequently, the paper briefly addresses the requirements of data sets over land and the ocean.

2. DATA SET REQUIREMENTS

2.1 ISCCP Programme

2.1.1 *Data Needed for ISCCP Validation*

Validation of the ISCCP cloud climatology involves two distinct issues: cloud detection and cloud property retrieval. Cloud detection leads to a climatology of cloud frequency-of-occurrence which provides an important characterization of the atmospheric/climate dynamics. With the data and analysis techniques available to ISCCP, cloud detection is especially difficult in three cases: polar regions, continental boundary layer cloudiness at night, and in mountainous terrain. Efforts to provide routine corroborative observations of clouds from the surface in these regions are important. Study of the utility of other satellite radiometer spectral channels for detecting clouds is more important because we wish to improve cloud detection capability permanently. Data sets needed for these studies:

(1) Ground-based observations of cloud occurrence in polar regions and in mountainous areas. (Data are available except for central Arctic and Himalayas.) These data sets should include simultaneous measurements of surface radiative properties.

(2) Better ground-based cloud detection at night. (Data are not generally available.)

(3) Multispectral satellite radiance data sets. (Operational weather satellite imaging data are available in the ISCCP archive. Other satellite data are in scattered archives.)

Retrieval of cloud properties from satellite-measured radiances requires a radiative model of clouds, atmosphere, and surface. Such a model is being used in the ISCCP analysis, but a number of model assumptions need to be checked in order to understand the significance of variations in the cloud parameters recorded in the ISCCP climatology. The two most important issues are the effect of cloud size distribution and cloud morphology on the retrievals and their interpretations. Data needed for these studies:

(1) Very high resolution, limited area, satellite imaging data covering sufficiently long time records to provide statistical cloud size distribution results and to allow tests of the effect of varying resolution on retrieved cloud parameters. (Some data are available in widely scattered archives, but special data sets need to be collected.)

(2) Simultaneous, coincident, multidirectional observations of various cloud types on scales from individual cloud elements up to mesoscale cloud fields. These observations, from combinations of ground-based, aircraft, and satellite radiometers, can be used to study the angular dependence of radiation coming from clouds, especially at cloud field scale. This type of study contributes to improved interpretation of cloud parameters retrieved from satellite data, but also allows extension of these observations to calculation of radiative fluxes. (Some data are available in the ISCCP archive [low resolution] and in scattered archives, but special efforts to collect higher quality examples of this type of data are needed.)

2.1.2 Data Needed to Extend ISCCP to Radiation Budgets

Improvement of our ability to model the interaction between clouds and radiation not only concerns interpretation of remote sensing data to study cloud properties, but also concerns calculation of the radiative consequences of cloud variations for weather and climate. Validation of ISCCP addresses the former concern, primarily, but additional studies can be used to extend ISCCP results to radiation budgets, especially planetary and surface. Key uncertainties in this type of calculation are in the cloud radiative model, radiative properties of snow and ice covered surfaces, and cloud vertical structure. Data sets needed for these studies:

(1) ERBE (and NIMBUS 7) radiation budget data (raw observations and analyses). Comparisons of narrowband and broadband radiance measurements from narrow and wide field of view instruments, as well as radiation budget components inferred from ERBE and ISCCP, provide ways to check the angular and spectral relationships in current cloud radiation models. (Data are available.)

(2) Ground-based and aircraft radiance and flux measurements, especially over snow and ice covered surfaces, coordinated with satellite observations to confirm calculations of downwelling radiation below clouds inferred from the satellite data. These data sets should also include observations of cloud base altitude/temperature and surface radiative properties to be compared with values inferred from satellite data. (Some data of this type are available, but special coordinated measurement programs are needed.)

(3) Vertical profiles of cloud properties and radiative fluxes. (Currently this type of data is not available.)

2.1.3 ISCCP Data Archive

The ISCCP data archive is located at NOAA/NESDIS and, thus, is associated with the complete satellite data holdings of NOAA. The specific ISCCP data holdings will include:

(1) Reduced resolution radiance images from all available operational weather satellites at a nominal 10 km, 3-hr resolution for geosynchronous satellites (GOES, GMS, METEOSAT) and GAC data from at least one polar orbiter. Data from all radiometer channels are present. Data collection began in July 1983.

(2) Reduced resolution radiance images (~30 km for all satellites) in uniform format with calibration and navigation information appended.

(3) Correlative data sets, including TOVS products, NMC surface station reports (only some quantities), and operational snow (NOAA) and sea ice (US Navy) reports, remapped into common map grids with only a modest amount of space and time interpolation (real data flagged).

(4) Cloud climatology products providing the equivalent of a complete atmospheric column description at each map location every 3 hrs that includes atmospheric temperature and humidity profiles, ozone column abundance, surface temperature and reflectance, cloud cover fraction (and uncertainty estimate), cloud optical thickness, cloud top temperature and pressure, and satellite-measured radiances. Additional cloud statistics and cloud classification information is provided, as well as general data sets used in the analysis, such as topography and vegetation classification. Several of these properties are effective radiative values; conversion to proper physical quantities may require further study or modeling.

2.2 Data Set Needs for TOGA and WOCE

Two major experiments within the World Climate Research Programme (WCRP) will require knowledge of the radiation budget at the ocean surface. These are the Tropical Ocean and Global Atmosphere (TOGA) experiment and the World Ocean Circulation Experiment (WOCE).

2.2.1 TOGA Programme

The TOGA programme will be focused on the study of the upper tropical ocean and the overlying atmosphere in order to understand, and eventually predict, the evolution of tropical ocean perturbations and the global atmospheric response. Within the overall WCRP one of the specific climate research problems addressed by TOGA is the determination of the air sea fluxes (of momentum, vorticity, heat, and water) and hence the coupling of the atmosphere with the tropical ocean. Obviously, in order to determine the ocean surface heat flux an estimate of the net surface radiation budget is required.

The only accuracy requirement for radiation data stated in the TOGA Scientific Plan is that for incoming shortwave radiation flux. The requirement is for an accuracy of 10 Wm^{-2} for monthly averages in each 2° latitude by 10° longitude box in the tropical zone (strictly $\pm 20^\circ$ latitude, but taken to be $\pm 30^\circ$ latitude in many studies). Concerning the net heat flux variations associated with the Pacific El Niño/Southern Oscillation (ENSO) phenomenon are of order 200 Wm^{-2} , an accuracy of 20 Wm^{-2} rms for the mean flux (averaged as defined above) would be appropriate, and an accuracy of 40 Wm^{-2} would still be useful. However, interannual variability in the tropical Atlantic and Indian Oceans is substantially less than in the Pacific. It would seem appropriate therefore to define, on a global basis, a benchmark accuracy of 10 Wm^{-2} for the space and time averaged surface net radiation budget (shortwave and longwave combined). Estimates to lower accuracy will still be valuable for TOGA research; however, the research goals may become more limited if lower precision is achieved.

Although the above accuracy requirements are defined in terms of monthly mean values, for some TOGA research projects data on higher time and space resolution are required. In general the surface radiation budget is not likely to be required at a resolution greater than one day or $2^\circ \text{ lat.} \times 2^\circ \text{ long.}$

Data availability is also an important consideration both in terms of timeliness and ease of access. Surface radiation budget estimates for TOGA should be available within 6 to 18 months of observation. Present planning envisages an Air-Sea Interface Data Centre producing fields of the mean surface fluxes as a non-real-time operational level 3 data product. The SRB data should be made available to this programme in level 2 (or level 3 on a standardized grid) form. The SRB database would form one node of a data-conduit-based data processing network. In the scheme proposed, individual researcher groups, or operational groups responsible for a particular product, each represent network nodes. The network nodes may interact directly, or more conveniently, through a "data conduit." The data conduit is a group (or node) whose purpose is to obtain and "package" the data in a convenient form for distribution to other nodes. There is also need for a data coordination group to collate and make available information concerning data availability. This group may be collocated with the data conduit, although this is not necessarily so.

The TOGA programme commenced on 1 January 1985 and will continue for 10 years. It is therefore important that consideration be given to obtaining the SRB retrospectively from the start of 1985.

2.2.2 WOCE Planning

WOCE planning centers on the availability, from about 1990, of satellites which will give greatly improved observations over the global oceans of variables such as wind stress and surface elevation, and also on the present rapid development of computer technology. The latter is important since it will allow higher resolution numerical modeling of the global oceans. One goal of WOCE is to collect the data necessary to develop and test ocean models useful for predicting climate change. It will also be necessary to determine the representativeness of the specific WOCE data sets for the long-term behaviour of the ocean, and to find methods for determining long-term changes in the ocean circulation.

The surface heat flux contributes to the forcing of the ocean thermohaline circulation and thus must be estimated as part of WOCE. Accuracy and data availability requirements for the SRB for WOCE purposes are similar to those for TOGA, and it is expected that WOCE data management will build on that developed for TOGA. Note, however, that WOCE requires monthly mean SRB data globally with 5° lat. \times 5° long. resolution (2° lat. \times 5° long. in the tropics). WOCE is planned to commence in 1990 and continue through 1994.

2.2.3 *Ground-Based Measurements*

Ironically, as interest has increased in the use of satellites for long-term climate-related studies (ISCCP, ISLSCP, etc.), interest and support for long-term surface measurements seems to be on the decline. NOAA, through the AgRISTARS Program, has collected, since August 1980, a set of GOES VISSR data at several hours per day from many of the NOAA SOLMET monitoring network sites. Simultaneous satellite and surface measurements of this type have served in developing the insolation algorithms in use by NOAA and would be valuable in other applications requiring calibration of the GOES VISSR sensor. Unfortunately, the availability of the surface data from the SOLMET sites is severely limited after December 1980, the only form readily available being microfiche copies of non-quality-controlled radiometer data.

The DOE-funded Solar Energy Meteorological Research and Training Site (SEMRTS) program provided operation of several university sites and collection of varying solar and terrestrial radiation parameters (global, direct, downwelling IR, UV, etc.). However, data from this program are only available through about 1982.

3. POSSIBLE DATA SETS

The most important data sets for surface radiation budget are listed below.

(1) Hourly (or at least 3 hourly) ground-based observations of low clouds and total cloudiness along with collaborating satellite observations of total cloudiness and low clouds (if possible).

(2) Low clouds to be classified into at least two groups—stratus and stratocumulus, and convective type.

(3) Low cloud base heights. For this data set it is essential that lidar observations at a few monitoring stations be scheduled for routine observations at a few representing places to cross validate ground-based data.

(4) Upward and downward radiative components at the surface are needed. These include: (a) downward solar irradiance—both direct and total, (b) upward reflected total solar radiation, and (c) net infrared radiation at the surface. These data need to be in a form that would be useful for eventual parameterization using satellite observations. The radiation budget observations, particularly albedo measurements of the surface and net infrared radiation need to be made over flat unobscured terrain (where possible). These values need to be checked periodically (cross validated) by suitably instrumented low flying aircraft. Such observations should be made both under clear and cloudy sky conditions. As discussed in WCP-70, the ground-based observations of solar data can be developed for use in parametric form applied to satellite observations.

(5) For application to surface heat budget climate studies, complementary to the surface radiation budget, it is still essential that a network of evaporation measurements—with an accuracy better than 10%—be developed. We still do not know the global (or even hemispheric) components of the hydrological balance; i.e., evaporation and precipitation to better than 15% and the geographic distribution is even less well known.

4. AVAILABLE DATA SETS

Global data sets are held in Leningrad, but there are major difficulties associated with obtaining the data. Regional and national data sets are held in local archives, and their quality varies between the individual centres. A US National Archive of Climate Data is available at Ashville, North Carolina. However, this archive does not include all the NASA data that may be used for climate studies. These data sets are held at the National Space Science Data Centre, Goddard Space Flight Center.

5. FUTURE REQUIREMENTS

Many of the available satellite (and other) data being collected that have nearly global coverage have not been analyzed or effectively used in the study of global atmospheric and surface processes. The single largest obstacle to research use of these data is lack of adequate documentation of format, calibration, and navigation. Improvement of data documentation, even without standardization, would make these data more accessible. The archives of global data held at Leningrad are unable to provide data in an effective manner, and still present the material only on paper.

Accessibility is also limited by lack of a central catalogue (or catalogues) that allows a researcher to discover what is already available. This catalogue must include information on instrument characteristics, time/space resolution and coverage, and a bibliography of previous uses/users. Creation of such catalogues for current data sets would be an important stimulant to data use.

A crucial shortcoming of existing data archives is that they are only passive storehouses. Lack of documentation means that data sets eventually "pass from our memory" and become useless. The interaction between users and archivers should be altered so that users, who learn something useful about the data set, are able and required to return their knowledge to the archive in the form of software, analyzed versions of the data, or both. In this way, the archive grows in value with time.

A major development in data archiving and dissemination has been by NASA (NSSDC—L. Treinish [Manager]) through the construction of the PILOT Data Analysis Systems. The Pilot Climate Data System (PCDS) provides a focal point for managing and providing access to a large collection of actively used data for the Earth, Ocean, and Atmospheric sciences. Uniform data catalogues, inventories, and access to methods for selected NASA and non-NASA data sets are available. The scientific community participating in the Workshop should consider how it may influence and assist in the management of the PCDS. Through high speed computer links, this system will allow access to the latest data storage and retrieval technology (e.g., video discs), and will provide, in principle, the foundation for an interactive data archive to support climate studies.

APPENDIX C

RELATED EFFORTS IN OTHER PROGRAMS

RELATED EFFORTS IN OTHER PROGRAMS

1. GENERAL

Efforts to measure the components of the surface radiation budget cannot be considered in isolation from efforts to measure other physical quantities relevant to climate. In all cases the scientific applications of the data are more or less closely related. In many cases the same basic data, e.g., satellite radiances, are involved in the determinations of the different physical quantities, and the methods by which the quantities are derived depend on physical models of radiative transfer in the atmosphere, which should be consistent. Also, some of the necessary validation experiments planned for one program may be useful in another. The programs we shall consider are: the Earth Radiation Budget Experiment (ERBE); the International Satellite Cloud Climatology Project (ISCCP); the International Satellite Land-Surface Climatology Project (ISLSCP); various ocean research programs (TOGA, WOCE); programs related to numerical modeling of the climate; operational services; and NASA's Pilot Climate Data System (PCDS).

2. ERBE

The Earth Radiation Budget Experiment (ERBE) is the latest of a series of NASA experiments (starting with the Nimbus missions) dedicated to the measurement of top-of-the-atmosphere (TOA) earth radiation budget components, and it is the first in which a multi-satellite system is used (ERBS, launched in October 1984; NOAA-9, launched in December 1984; and NOAA-G, to be launched spring 1986) to obtain adequate sampling of diurnal variations. Operations are to extend through 1988. The products are to include monthly mean values of the ERB components at the top of the atmosphere on spatial scales ranging from $2.5^\circ \times 2.5^\circ$ regions to global; monthly mean diurnal variation is also to be determined on these scales. Spectral discrimination is made between the thermal (LW) and solar (SW) domains and absolute accuracy is expected to be very good. In some cases the correlation of the radiation budget components at both boundaries of the atmosphere can be significant and should be investigated. In all cases the differences between these components at the surface and top of the atmosphere give the forcing of atmospheric dynamics by radiation, a quantity of fundamental interest.

3. INTERNATIONAL SATELLITE CLOUD CLIMATOLOGY PROJECT (ISCCP)

The principal modulators of the downward components of the surface radiation budget are clouds. Since mid-1983 the ISCCP has been underway to improve our knowledge of these (Schiffer and Rossow, 1983, 1985). Data from each of the five geostationary meteorological satellites and the two NOAA polar orbiters are being sampled temporally (every 3 hours) and spatially (1 pixel of about 4–8 km, about every 30 km), and combined in a global archive of inter-normalized satellite radiances in the solar and infrared window bands (and others where available, such as the $6.3 \mu\text{m}$ "water-vapor" band of Meteosat). Archived with the global B3 data set of ISCCP are some correlative data such as TOVS products. This data set is being produced now at NASA GISS and is available through NOAA/NESDIS. On sufficiently large spatial scales, it can serve as the "raw material" for algorithms using the satellite radiances for determinations of the radiation budget at the surface, and because of the manageable size of this data set, it can be used by research groups and not only by large operational services. (A second version of these data with about 10 km resolution is also archived at NOAA/NESDIS.)

It should be noted that the objective of ISCCP is a global *cloud* climatology; provisional algorithms for extracting cloud parameters (amount, cloud top temperature, etc.) are being applied to the B3 data set by the Global Processing Center (NASA GISS) and by several research groups. The

cloud archive may be a suitable input for some SRB methods that use cloud parameters explicitly (together with other data) for determination of the surface radiation budget. Ultimately the cloud archive will include information based on surface data as well as satellite data, in which case it would include more reliable estimates of cloud base height, which would enhance its usefulness for SRB determination.

Considerable validation efforts for ISCCP are being planned. Notably the FIRE (First ISCCP Regional Experiment) will involve campaigns of intense surface and in situ measurements. Some of these data may be of use in the SRB validation studies, and in future experiments plans should be made to include instruments relevant to SRB as well as clouds.

4. INTERNATIONAL SATELLITE LAND-SURFACE CLIMATOLOGY PROJECT (ISLSCP)

The upward SRB components depend on both "permanent" and varying surface properties. The International Satellite Land-Surface Climatology Program is being organized, with support by WCRP, COSPAR, and UNEP to develop a system for global monitoring of at least some of these properties for the continents. For example, surface albedo can be viewed as a surface property, to be monitored in ISLSCP, as a factor influencing climate or as a property impacted by climate, or both as in the Charney feedback mechanism. It is, of course, also an element of the surface radiation budget. In some methods for determining the radiation at ground it is assumed to be constant (although perhaps solar zenith angle dependent) over say a month.

More generally, the determination of land surface properties from satellites involves the choice of spectral channels in which atmospheric effects are minimized. These are therefore also useful for the determination of upward components of the surface radiation budget. Furthermore, since some atmospheric correction procedures involve modeling of atmospheric properties, they may be of use in estimating downward SRB components through radiation transfer modeling methods.

There is much interest in the ISLSCP participating groups in the use of the diurnal cycle of surface temperature, estimated from the IR window channel data from geostationary satellites, to study surface-atmosphere heat and moisture exchange. The field experiments (e.g., FIFE) being envisaged require determinations of all SRB components. Thus the validation of experimental satellite SRB determinations over land, can be in many cases part of ISLSCP validation exercises and planning should be coordinated.

5. OCEAN RESEARCH PROGRAMS

The TOGA (Tropical Ocean and Global Atmosphere) experiment requires estimates of the surface radiation budget components. If, as suspected from GATE and other results, the longwave net radiation at tropical sea surfaces is small (Fung et al., 1984), the requirement is for an estimate of the downward solar radiation and its reflected portion as well. To the extent that appropriately instrumented research vessels are available during TOGA, these afford opportunities for validation of satellite determinations of SW at the sea surface.

Sea-surface temperature (SST) determinations are another important component of TOGA and other ocean research programs, and they are being produced more or less routinely by the satellite operators using the infrared window data and some form of atmospheric correction. Since sea-surface emissivity is known, this amounts to a comfortable determination of the upward emission at least for all oceans and cloud-free continental areas. The atmospheric correction procedure involves information which can help to estimate the clear sky downward longwave radiation although it may not be sufficient.

To study ocean-atmospheric energy exchange outside the tropics (WOCE), and whenever the atmosphere is dry in the tropics, determination of all four components of the surface radiation budget is required. This difficult question cannot be eluded.

6. NUMERICAL MODELING

In some methods for SRB determination, numerical radiative transfer modeling is used to estimate downward longwave fluxes. Alternatively, if reliable independent SRB data were available, one could encourage using them to validate climate-model-predicted SRB as well as TOA ERB. However, both procedures require confidence in the radiative transfer calculations performed. Doubts on the model accuracy have arisen, and the ICRCM is being carried out and has already shown that further studies are necessary. It may, however, also be useful to produce a global SRB data set from model output, e.g., at the ECMWF, for comparison with other data sets produced by using bulk formulas.

7. OPERATIONAL SERVICES

As already noted, operational meteorological services are engaged in producing SST estimates; some may soon be producing estimates of the downward solar radiation on a routine basis, at least over limited areas. Other products related to SRB exist such as the vegetation indices. On a more fundamental level, the NOAA AVHRR GAC and TOVS products are archived and available, for studies for which the ISCCP B3 spatial sampling is not sufficiently dense. Some full-resolution geostationary satellite data (e.g., 2 or 3 channels, every half hour) from Meteosat, available from ESOC (Darmstadt), is also being archived and so if available is necessary to SRB groups which can afford to buy and handle the data.

8. NASA PILOT CLIMATE AND PILOT LAND DATA SYSTEMS

The goal of the NASA Pilot Climate and Pilot Land Data Systems (PCDS and PLDS) is to provide an understanding of and to implement solutions to various technical problems involved in providing unified data management support for selected climate-related data. This system provides insight into the validity of these solutions via direct interactions between the PCDS and the user community. The PCDS will evolve to form a base line information management system to which further climate data management support can be added. In concept, the initial thrust of the PCDS effort is to provide comprehensive information describing selected NASA climate-related data, flexible easy access to data of interest, and delivery of data products in readily usable form. The PCDS, implemented initially with limited climate data coverage, provides a basic capability for later expansion and augmentation. It serves both to demonstrate the feasibility of establishing a centrally managed NASA climate data base, and to test developments in evolving a comprehensive capability for providing unified, flexible access to a variety of climate parameter data sets derived from various instruments and sources.

The PCDS is an interactive, scientific information management system for locating, obtaining, manipulating, and displaying climate-research data. The PCDS was developed, and continues to be enhanced, to manage a large collection of data of interest to NASA's research community, and currently provides such support for twenty data sets. Among these data sets are Nimbus-7 ERB-MATRIX, ERB-ZMT, ERB-SEFDT, and LIMS-LAMAT; FGGE II-c (ERB-MATRIX, ERB-ZMT, LIMS, and SMMR), II-b, and III-b (ECMWF); NMC Octagonal Grids; NOAA Heat Budget; and World Monthly Surface Station Climatology which contain parameters of interest for surface radiation budget studies. The PCDS enables researchers to locate data of interest, preview data using graphical and statistical methods, and extract subsets for further analysis at their own sites. The PCDS resides

on a DEC VAX-11/780 computer system located at NASA's Goddard Space Flight Center in Greenbelt, Maryland. Access to the PCDS is provided via dial-up and network terminals, as well as direct lines.

The PCDS allows both the local and remote user to perform the following functions: (1) obtain comprehensive descriptions of a number of climate parameter data sets and the associated sensor measurements from which they were derived, many of which include discussions of radiation budget data; (2) obtain detailed information about the temporal coverage and data volume of data sets which are readily accessible via the PCDS; (3) extract portions of a data set using criteria such as time range and geographic location, and output the data to on-line disk files in a special data-set-independent format (PCDS Climate Data File, CDF) to a user terminal, to a system printer, or to a tape; (4) access and manipulate the data in this CDF format and perform such functions as combining the data, creating a subset of the data, or averaging the data; and (5) create various graphical representations of the data stored in the CDF format.

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APPENDIX D

LIST OF SHORT PRESENTATIONS

LIST OF SHORT PRESENTATIONS

- Global Radiation From Satellite Data at Different Spatial Scales
E. Raschke, University of Koln, Germany
- Satellite-Based Estimates of Solar and Net Radiation at the Ocean Surface
John E. Hay, University of British Columbia, Canada
- Results on Shortwave Surface Radiation Over the Ocean From GOES Observations
C. Gautier, Scripps Institution of Oceanography, La Jolla, California
- Determination of Surface Radiation Budget From Satellite Measurements
Wayne L. Darnell, NASA Langley Research Center, Hampton, Virginia
- Surface Radiation Budget
Rachel T. Pinker, University of Maryland, College Park, Maryland
- Longwave Surface Radiation Budget Using Meteosat Data
Johannes Schmetz, ESA/ESOC, Germany
- Longwave Surface Radiation Over the Oceans From Satellite Observations
Robert Frouin, Scripps Institution of Oceanography, La Jolla, California
- CLAIRE: Preliminary Design of a Clear Air Infrared Radiation Experiment
Warren Wiscombe, NASA Goddard Space Flight Center, Greenbelt, Maryland
- Surface Radiation Experiments in Sonora Desert
Charles H. Whitlock, NASA Langley Research Center, Hampton, Virginia
- Canopy Spectral Reflectance, Photosynthesis and the Energy Budget
P. Sellers, NASA Goddard Space Flight Center, Greenbelt, Maryland
- Sensitivity Study
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APPENDIX E

ACRONYM LIST

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AES	Atmospheric Environment Service (Canada)
ALPEX	Alpine Experiment
ASAP	Automated Shipborne Aerological Program
ATS	Applications Technology Satellite
AVCSR	Airborne Version Conical Scan Radiometer
AVHRR	Advanced Very High Resolution Radiometer
BRDF	Bidirectional Reflectance Distribution Function
CCM	Community Climate Model
CDF	Climate Data File
CLAIRE	Clear Air Infrared Radiation Experiment
COSPAR	Committee on Space Research
DOE	Department of Energy
EC	European Community
ECMWF	European Centre for Medium Range Weather Forecasts
ENSO	El Niño/Southern Oscillation
ERB	Earth Radiation Budget
ERBE	Earth Radiation Budget Experiment
ERBS	Earth Radiation Budget Satellite
ESOC	European Space Operations Center
FASINEX	Frontal Air-Sea Interaction Experiment
FGGE	First GARP Global Experiment
FIFE	First ISLSCP Field Experiment
FIRE	First ISCCP Regional Experiment
GAC	Global Area Coverage
GARP	Global Atmospheric Research Program
GATE	GARP Atlantic Tropical Experiment
GCM	General Circulation Model
GISS	Goddard Institute for Space Studies
GMCC	Geophysical Monitoring for Climate Change
GMS	Geostationary Meteorological Satellite
GOES	Geostationary Operational Environmental Satellite
GOES-NEXT	Next Generation GOES System
HEX-MAX	Humidity Exchange Over the Sea Experiment–Main Experiment
HIRS	High Resolution Infrared Sounder
IAMAP	International Association of Meteorology and Atmospheric Physics
ICRCCM	Intercomparison of Radiation Codes in Climate Models
IEA	International Energy Agency
IGOSS	Integrated Global Ocean Services System
IR	Infrared
ISCCP	International Satellite Cloud Climatology Project
ISLSCP	International Satellite Land-Surface Climatology Project
JASIN	Joint Air-Sea Interaction Experiment
JSC	Joint Scientific Committee
LBL	Line-by-Line
LIMS	Limb Infrared Monitor of the Stratosphere
LW	Longwave
MILDEX	Mixed Layer Dynamic Experiment
MIZEX	Marginal Ice Zone Experiment
MONEX	Monsoon Experiment

MSU	Microwave Sounding Unit
NASA	National Aeronautics and Space Administration
NCAR	National Center for Atmospheric Research
NESDIS	National Earth Satellite, Data, and Information Service
NESS	National Earth Satellite Service (now NESDIS)
NMC	National Meteorological Center
NOAA	National Oceanic and Atmospheric Administration
NRC	National Radiation Center
PCDS	Pilot Climate Data System
PLDS	Pilot Land Data System
rms	Root Mean Square
SEFDT	Solar and Earth Flux Data Tape
SEMRTS	Solar Energy Meteorological Research and Training Site
SMMR	Scanning Multichannel Microwave Radiometer
SMS	Synchronous Meteorological Satellite
SRB	Surface Radiation Budget
SRBC	Surface Radiation Budget Center
SST	Sea-Surface Temperature
STORM	Stormscale Operational and Research Meteorology
STREX	Storm Transfer Region Experiment
SW	Shortwave
TIROS	Television and Infrared Operational Satellite
TOA	Top of the Atmosphere
TOGA	Tropical Ocean and Global Atmosphere
TOVS	TIROS Operational Vertical Sounder
UNEP	United Nations Environmental Program
VAS	VISSR Atmospheric Sounder
VISSR	Visible and Infrared Spin Scan Radiometer
WCP	World Climate Program
WCRP	World Climate Research Program
WG	Working Group
WMO	World Meteorological Organization
WMO-CIMO	WMO Commission on Instruments and Methods of Observation
WOCE	World Ocean Circulation Experiment
WRC	World Radiation Center
WRDC	World Radiation Data Center
WWW	World Weather Watch
XBT	Expendable Bathythermograph

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16. Abstract This report presents results from the Workshop on Surface Radiation Budget (SRB) for Climate Applications, held at Columbia, Maryland, on June 18-21, 1985. The SRB consists of the upwelling and downwelling radiation fluxes at the surface, separately determined for the broadband shortwave (SW) (0-5 μm) and longwave (LW) (greater than 5 μm) spectral regions plus certain key parameters that control these fluxes, specifically, SW albedo, LW emissivity, and surface temperature. The workshop, which was jointly sponsored by NASA, the World Climate Research Program, and the International Association of Meteorology and Atmospheric Physics, brought together leading scientists with expertise in the theory and measurement of surface radiation by satellite and ground-based systems. Results include the uses and requirements for SRB data, critical assessment of current capabilities for producing these data, and directions for future research.			
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